FIRAT UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
T Ü R K İ Y E

HYDROGEOLOGICAL INVESTIGATION OF THE CENTRAL PART (CENTRAL SUB-BASIN) OF THE ERBIL BASIN (NORTH OF IRAQ)

Nashwan Jalal Smail KHOSHNAW

Master's Thesis

DEPARTMENT OF GEOLOGICAL ENGINEERING
Division of Hydrogeology

JULY 2022

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THESIS APPROVAL

This thesis, which was prepared according to the thesis writing rules of the Graduate School of Natural and Applied Sciences, Fırat University, was evaluated by the committee members who have signed the following signatures and was unanimously approved after the defense exam made open to the academic audience.

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DECLARATION

I hereby declare that I wrote this Master's Thesis titled "Hydrogeological Investigation Of The Central Part (Central Sub-Basin) Of The Erbil Basin (North Of Iraq) " in consistent with the thesis writing guide of the Graduate School of Natural and Applied Sciences, Firat University. I also declare that all information in it is correct, that I acted according to scientific ethics in producing and presenting the findings, cited all the references I used, express all institutions or organizations or persons who supported the thesis financially. I have never used the data and information I provide here in order to get a degree in any way.

04 July 2022

Nashwan Jalal Smail KHOSHNAW

PREFACE

In the Erbil central sub-basin, the amount of extracted water is ten times more than the amount of water feeding into the sub-basin and the aquifer is not annual renewable storage, and it is very difficult to store it again. There is a huge number of licensed and unlicensed wells that have been drilled in the central sub-basin compared to other sub-basin of the Erbil basin in recent years. There is no detailed scientific research on the hydrogeological aspect of the study area. Therefore, it is necessary to reveal the current hydrogeological conditions of the basin. In light of the hydrogeological data that will be obtained in this study, the current hydrogeological parameters of the basin will be compared with those observed in previous years, and the necessary precautions will be determined to ensure the sustainability of the groundwater potential in the area.

I thank God for giving me the strength and ability to complete this study. I would like to express my sincere appreciation to my supervisor, Assistant Professor Dr. Özlem Öztkin Okan for her excellent guidance, interest and patience, and for providing an excellent atmosphere for conducting research. And a special thanks to all my colleagues in the Erbil Groundwater Directorate for their support in the field of hydrogeology (rock description, well monitoring, pumping tests, water level monitoring). Finally and most importantly, I would like to thank my wife Sulin Abdal Mahmoud for her support, encouragement, calm patience and tolerance, and thank my mother, brothers and children for their spiritual support and faith throughout my life. In myself. Under their watchful eyes, I gained a lot of motivation and the ability to take challenges head on. I also thank all my friends. And everyone who helped me directly or indirectly.

Nashwan Jalal Smail KHOSHNAW
ELAZIG, 2022

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ABSTRACT

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The study area covers an area of about 1400 km², which is the central part of the Erbil Basin. The subject of the present thesis is to understand the current groundwater level in the aquifers (confined and unconfined aquifers) in the central part of Erbil Basin (central sub-basin), and to determine the possible factors for the fluctuations.

The basin is caused by step sliding which in turn, causes the basin to hold more Quaternary deposits of more than 350 m making high productive aquifers. The annual rainfall is around 392 mm, of which 92% of this precipitation occurs from December to March. The statistical analyses showed the annual precipitation general trend is declining in contrast to a temperature which raised 1°C from 2001 to 2021. The morphometric analysis indicates homogenous deposits, materials subjected to weathering and erosion, high permeability, and low relief. Various methods have been applied to estimate the hydrogeological properties of aquifers. The groundwater levels in 24 wells that were located in the Erbil Central sub-basin were measured during one year by using a sounder. The hydraulic conductivity, transmissivity, and storage coefficient of the aquifers were calculated by using AQTESOLV software related to the results of pumping tests of 24 wells. Pumping test data of time-drawdown and well information shows the basin is dominant of unconfined system, while parts of the basin have locally confining beds. The transmissivity is ranged from 0.52 to 183.3 m²/d, the specific yield ranged from 0.088 to 0.281, the hydraulic conductivity is between 0.0027 to 1.1315 m/day, and the storage coefficient is between 0.0128 to 6.386.

Long-term water table fluctuation showed a decline of the water table from an average of 62 m from 2001 to 2021 and showed that the middle of the area is more sensitive. A number of factors cause groundwater table fluctuations in the study area. The reasons are; (i) climate change has had a negative impact on the study area, (ii) variations in rainfall amount and pattern it has an impact on the amount of recharge water entering the groundwater, and (iii) if there is a long period between two dry periods, (iv) rain-fed crops will absorb a large portion of the incoming rainstorms that results the reducing of infiltrated rainwater percolation, (v) changes in land use due to urbanization, industrialization, agricultural lands, and (vi) leakage of groundwater flowing to adjacent basins or rivers, and (vii) excessive exploitation.

Keywords: Erbil Basin, Hydrogeology, Groundwater Fluctuation, Seasonal Variation, Unconfined Aquifer.

ÖZET

Erbil Havzası Orta Bölümünün (Orta Alt Havzası) (Irak'ın Kuzeyi) Hidrojeolojik İncelemesi

Nashwan Jalal Smail KHOSHNAW

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Çalışma alanı, Erbil Havzası'nın orta kısmı olan yaklaşık 1400 km²'lik bir alanı kaplamaktadır. Bu tezin konusu, Erbil Havzası'nın orta kesiminde bulunan akiferlerin (serbest ve basınçlı akiferler) mevcut yeraltı suyu seviyesini belirleyerek, yeraltı suyu seviyesinde meydana gelen dalgalanmaların nedenlerini araştırmaktır.

Havza, kayma hareketlerine bağlı olarak kademeli bir yapı kazanmıştır, bu da havzanın 350 m'den daha fazla Kuvaterner yaşlı sediman ile dolmasına ve verimi yüksek akiferlerin oluşturmasına neden olur. Bölgede yıllık yağış miktarı 392 mm civarındadır ve bu yağışın %92'si Aralık'tan Mart'a kadar gerçekleşir. İstatistiksel analizler, 2001- 2021 yılları arasında sıcaklığın 1°C yükselmesinin aksine yıllık yağış miktarının düştüğünü göstermektedir. Morfometrik analiz sonuçları, Kuvaterner yaşlı sedimanların düşük relyefe sahip olduğunu, çoğunlukla erozyon ve ayrışma ile oluşan malzemeden meydana geldiklerini göstermektedir. Kuvaterner yaşlı sedimanların geçirimlilikleri de oldukça yüksektir. Akiferlerin hidrojeolojik özelliklerini tahmin etmek için çeşitli yöntemler kullanılmıştır. Erbil merkezi alt havzasında yer alan 24 kuyudaki yeraltı suyu seviyeleri bir yıl boyunca kuyu düdüğü kullanılarak ölçülmüştür. Bu kuyulara ait pompaj kuyu testleri yardımıyla ve AQTESOLV bilgisayar programı kullanılarak akiferlerin hidrolik iletkenlik, transmisivitesi ve depolama katsayıları hesaplanmıştır. Pompaj deneyi verilerinin değerlendirilmesi sonucunda Kuvaterner çökellerinin transmisivitesi 0,52 ile 183,3 m²/gün arasında, özgül verimi 0,088 ile 0,281 arasında, hidrolik iletkenlikleri 0,0027 ile 1,1315 m/gün arasında ve depolama katsayısı 0.0128 ile 6.386 arasında hesaplanmıştır. Kuyu log verileri ile pompaj testlerine göre havzada serbest akiferlerin baskın olduğu, havzanın bazı kesimlerinde ise basınçlı akiferlerin olduğu belirlenmiştir.

Havzada, 2001 ile 2021 yılları arasında, serbest akiferlerin uzun vadeli su tablası hareketleri incelendiğinde, bu yıllar arasında su tablasının ortalama 62 m'lik bir düşüş gösterdiği belirlenmiştir. Özellikle havzanın orta bölümünde su tablası dalgalanmalarının daha fazla olduğu tespit edilmiştir. Yeraltı su seviyesinde meydana gelen dalgalanmaların çeşitli sebepleri bulunmaktadır. Bunlar: (i) küresel iklim değişimi, (ii) yağış miktarı ve modelinin yeraltı suyunu besleme durumu ve miktarı üzerindeki etkisi, (iii) iki kurak dönem arasındaki zamanın uzun olması, (iv) yağmurla beslenen mahsullerin yağışın büyük bir bölümünü emmesi bunun sonucunda toprağa yağmur suyu sızıntısının azalması, (v) kentleşme, sanayileşme, tarım arazileri vb. gibi nedenlerle oluşan arazi kullanımındaki değişimler, (vi) havzadaki yeraltı suyunun bitişik havzalara veya nehirlere doğru yönelimleri, yeraltı suyunun havza dışına sızması ve (vii) yeraltı suyunun aşırı pompajıdır.

Anahtar Kelimeler: Erbil Havzası, Hidrojeoloji, Yeraltı Su Seviye Değişimi, Mevsimsel Değişim, Serbest Akifer

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SYMBOLS AND ABBREVIATIONS

Symbols

P : Precipitation (mm)
Rh% : Relative humidity
T : Temperature (ºC)
E : Evaporation (mm/day)
PET : Potential evapotranspiration (mm)
WS : Water Surplus
WD : Water Deficit
AET : Actual evapotranspiration
Rs : Surface runoff
I : Infiltration
Q : Runoff (mm)
Re : Recharge
K : Hydraulic conductivity (m/day)
V : Groundwater velocity (m/day)
dh/dl : Hydraulic gradient
T : Transmissivity (m^2/d)
B : Saturated thickness (L)
S : Represents storativity.
V : The amount of water obtained or lost.
Sy : Specific yield
Δs : Difference of drawdown per log cycle t.
S* : Correction drawdown (m)
S : Drawdown value (m)
t/to : Time of last record / initial time
Sc : Specific Capacity

Abbreviations

S.W.L: Static water level (m)
D.W.L: Dynamic water level (m)

1. INTRODUCTION

In most countries groundwater as a result of an ever increasing demand is considered a major natural resource. The efficient exploitation of groundwater requires the possibility of predicting the variation of the resources and consequently of the groundwater levels for particular conditions of supply and withdrawal. The main scientific problem of the present study is to understand the main reasons for the groundwater level fluctuation in the aquifers in the Erbil Central sub-basin.

The subject of the present thesis is to understand the current groundwater level in the aquifers (confined and unconfined aquifers) in the central part of Erbil Basin (central sub-basin), and to determine the possible factors for the fluctuations. The changes in the amount of precipitation, drilling of a large number of wells in the basin, and excessive pumping from the wells are the major hypothesis for groundwater level fluctuation in the Erbil Central sub-basin.

Groundwater is the main and most important water resource in the Erbil plain, and it is used for a variety of purposes. Because of the Kurdistan region's thriving economy, the demand for groundwater is growing by the day. Khanates are one of the area's oldest groundwater exploitations, with ancestors digging horizontally underground tunnels from high elevation areas with high hydraulic heads to lower elevations with hydraulic heads extending many kilometers for domestic consumption and irrigation. Especially during the dry seasons, in addition to economic development, climate change is causing a continuous increase in the demand for water (both groundwater and surface water), global warming and the increasing effects of greenhouse gases have negatively affected the climate elements in the region, particularly the precipitation rate and pattern (Naqshbandi, 2008; Qurtas, 2013). These phenomena cause rain-fed crops (particularly barley and wheat) to grow less than in previous years. This causes farmers to look for alternative water sources, and most of the time, farmers drill wells to exploit groundwater as the only alternative to rain. Wells have been drilled in a variety of ways and for a variety of purposes. Many different machines and rigs were used to dig wells, including rotary, cable, and air compressor hummers and trench shovels. Wells were dug to various depths and diameters, ranging from a few centimeters to several meters (trench). All of these wells have been dug in both legal and illegal ways. Aquifer conditions, hydraulic properties of aquifers, probable recharge from precipitation, evapotranspiration due to climate elements, effects of discharge on water levels, and prediction of groundwater conditions scenarios are all part of this study. The study's main goal is to model current groundwater conditions in order to make the best decisions and develop groundwater strategies in light of current and future rapid changes in all economic sectors (agriculture, urban, and industrial).

Groundwater-level fluctuations due to aquifer storage changes involve either the addition or extraction of water from the aquifer, both through natural means and human involvement. Climate change and its impacts, on the one hand, include a decrease in precipitation, an increase in the number of hot days per year, and a change in the pattern of precipitation and rainy seasons on the other hand. In most countries, groundwater as a result of an ever-increasing demand is considered a major natural resource. The efficient exploitation of groundwater requires the possibility of predicting the variation of the resources and consequently of the groundwater levels for particular conditions of supply and withdrawal.

The aquifer is not a renewable annual storage, and storing it again is very difficult. The amount of extracted water is ten times more than the amount of water that recharges the central sub-basin of the Erbil Basin. There are many licensed and unlicensed wells drilled in the central sub-basin compared to other sub-basins of the Erbil basin, in recent years. There is no actual scientific research that has been performed on the hydrogeological aspect in the study area. Therefore, it is necessary to reveal the current hydrogeological conditions of the basin, in the light of the hydrogeological data that will be gained in the present study. The basin’s present hydrogeological parameters (such as groundwater level conditions, the permeability, and the transmissivity of aquifers) with those observed in the previous years will be compared, and the necessary precautions to ensure the sustainability of the groundwater potential of the central sub-basin will be determined.

1.1. Location of Study Area

The study area (Erbil Central sub-basin) is located in the north of Iraq, within the Erbil plain, which covers an area of about 1400 km^2. The Erbil city area is about 70 km^2 and is located between 36° 08' 30" - 36°14' 15" north latitudes and 43° 57' 30 "- 44° 03' 20" east longitudes (Figure 1.1). The northern boundary is the Kapran sub-basin, which has the highest elevation (more than 680 m) in the entire studied area and is relatively flat and plain, and the southern boundary is the Bashtapa sub-basin (Figure 1.2).

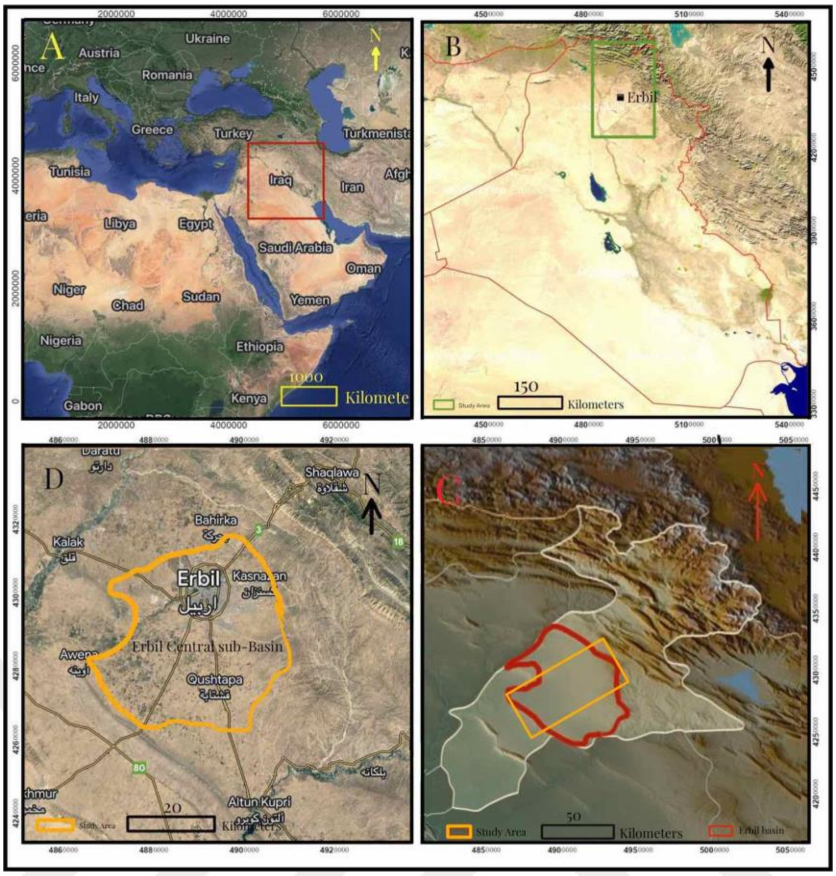

Figure 1.1. Location maps of the study area.

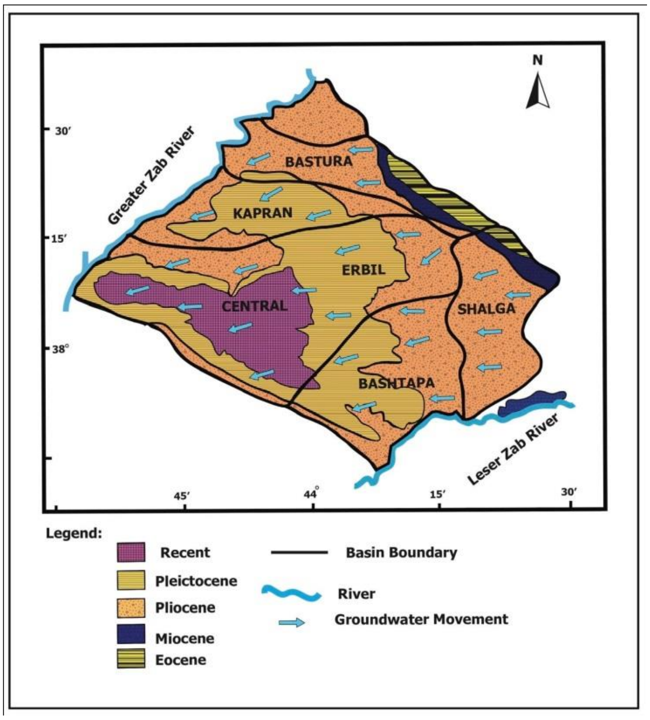

Figure 1.2. Hydrogeological sub-basins of Erbil (modified from Hameed, 2013).

The studied area is relatively flat and plain, with slopes in the eastern and northeastern parts and covered by Quaternary deposits. In the governorate of Erbil, more than 9,310 legal wells have been drilled. The majority of these wells are located in the Erbil Basin region. The number of wells dug in the Erbil Central sub-basin is 4,310 legal wells, and nearly 2,500 illegal wells have been registered (as recorded in the Erbil Groundwater Database, 2022).

1.2. Previous Studies

The history of groundwater investigation in the area belongs to thousand years ago, by dug wells and underground water tunnels and large-diameter wells. But the geological investigation in the area started in early 1920 during searching for oil and gas. Many works have been done in the last century (20th century) by international and national companies in the study area for research and investigations to assess the groundwater estimation, quality, sediments bearing water, modeling, and regional hydrogeology.

In 1959 an important work had done by Ralph M. Parsons Company. The company investigated groundwater in Erbil liwa through the geological and hydrogeological data at that time. The work was regional to evaluate the groundwater condition, recharge, and water balance for most potential groundwater exploitation.

From 1973 to 1975 very important works had done by Institute for Applied Researches on Natural Resources (IARNR) by national and international experts as a part of the UNDP project to study the hydrogeological condition of Erbil plain, collect data on groundwater resources, and evaluate the possibility of different agricultural crops, depending on supplementary irrigation depending on groundwater.

In 1978 Bosscher and Boonestra developed a hydrogeological model for the Erbil basin to analyze water well productivity.

Hassan A. H. (1981) studied "Hydrogeological condition of central Erbil basin" emphasizing the water quality. He also wrote with Jawad Sadik B. (1983) and C. P. Griolet (1982) about "the use of chloride concentration in groundwater as an indicator of the aquifer permeability (applied to the Erbil basin, 1982)". He also wrote with Natiq A. Zeki (1982) "Water Availability periods and water balance parameters" 1982 within the project of detailed hydrogeology for the Erbil basin.

Al-Azzawi (1983) elaborated a groundwater map for Erbil as a contour line groundwater map using lithology of wells through loggings. In 1983 the Furat center for Research and construction of irrigation projects prepared a report about the investment of groundwater in Erbil plain, estimating the storage value of Erbil sub-basins in relation to water level fluctuation.

Hassan I. O. (1998) Studied the Urban Hydrogeology of Erbil City Region, presented the groundwater recharge from rainfall, hydrological and hydrogeological condition of the Erbil city, the water quality, the water pollution through many sources, finally, he build a mathematical model to predict the water level for the next coming 12 years.

Ghaib F. A. (2000) used geophysical data by the two methods, gravity and magnetic, had made some geological profiles crossing the Erbil plain and the study area, he analyzed the lithology, stratigraphy, and structural geology of the area, and also hydrogeological properties of the aquifer and their thickness.

Hassan and Qurtas (2001) under the Oil For Food Program of FAO - UN, prepared a report about the infiltration of Erbil plain depending on field tests.

Stevanovic and Markovic (2003) researched the climate, hydrology, geomorphology, and regional geology of the three northern governorates "Sulaimani, Erbil, and Dohuk" in the first volume of a comprehensive program of FAO projects.”

Stevanovic and Markovic (2004) researched the overall hydrogeology and aquifer system of the three northern governorates "Sulaimani, Erbil, and Dohuk" in the second volume of their studies as part of a comprehensive program of FAO projects.

Bapeer et. al., (2010) have conducted a study work under the title of "infiltration rates of soils in some locations within Erbil plain, Kurdistan region, northern Iraq". They have taken a couple of locations to estimate the infiltration capacities and coefficient of permeability with determining probable recharging areas.

Qurtas, (2013), studied the groundwater evaluation and management using mathematical models for Shamamik Basin, the optimum management of the groundwater to suggest the best way of water exploitation taking in consideration the recharge value and increasing demand on water due to growth of population, development of economic sectors, and also negatively affecting factors of more urbanization and climate changes.

2. MATERIAL AND METHOD

2.1. Pre-Field Work

At the start of this study, all available data from various sources, as well as topographic and geological maps with appropriate scales for the area, and satellite images for mapping, documentation of drilled wells, and meteorological data (precipitation, relative humidity, temperature, wind speed, and evaporation) were gathered. The data lithological columns from drilled wells and well tests were collected from Erbil's Groundwater Directorate.

2.2. Field Work

A detailed geological survey of the entire basin and some surrounding areas were performed inculuding the mapping of geological formations, structures, and geomorphological features. Totally 24 wells' groundwater levels were monitored during one year beginning from October, 2020 until the end of October, 2021. The coordinates of the monitored wells were determined by the GPS instrument with UTM system (Table 2.1). The locations of the wells were shown on Figure 2.1.

Table 2.1. Locations of the investigated wells (data were collected from Groundwater Directorate of Erbil)

No	Well Name	GPS Coor. (UTM) X	GPS Coor. (UTM) Y	Elevation (m)
W01	Qoritan Chukul	405405	3993247	317.00
W02	Tandura -1	395403	3993029	315.00
W03	Mastawa	393525	3989963	308.00
W04	Shekh Sherwan	385953	3989337	293.00
W05	Grd Azaban	394916	3985193	303.00
W06	Perdawood	403046	3986980	340.00
W07	Satoor-1	391868	4004653	440.00
W08	Dugrdkan	405007	3981457	350.00
W09	Murtka Shahab	412718	3988467	408.00
W10	Bestanay Gawra	426966	3987635	599.00
W11	Grd Mala-3	415045	3982303	423.00
W12	Qushtapa-12	413469	3982303	413.00
W13	Qultapa Yaba	412812	3979755	402.00
W14	Nawroz-13	407630	4003043	396.00
W15	Shadi-23	407808	4001980	398.00
W16	Bakhe Shar Park	411158	4005256	415.00
W17	C.Science-1	411772	4001204	422.00
W18	Bahar-4	408874	4002102	406.00
W19	Shorsh-8	412704	4008359	443.00
W20	Daratw-53	412561	3998602	433.00
W21	Grda Rasha-4	411968	3995054	422.00
W22	Shawais-10	417583	4012229	518.00
W23	Kasnazan-7	422639	4007342	627
W24	Sebirany Gawra	402134	4012027	380

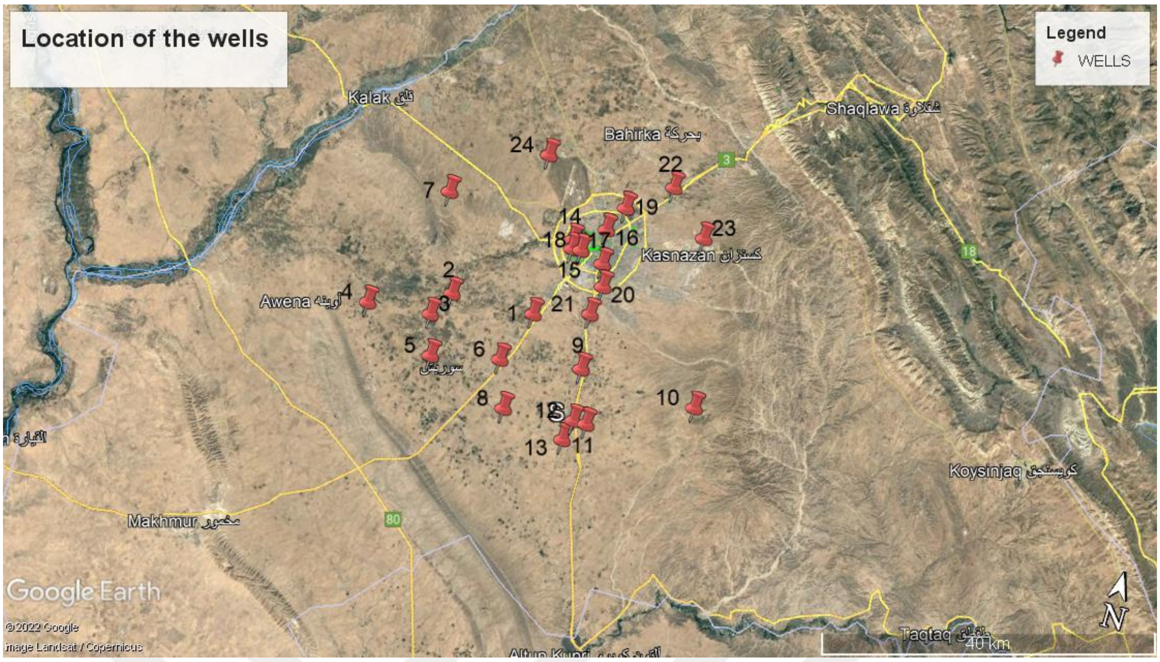

Figure 2.1. Locations of the monitored wells in the study area (Google Earth pro image)

The border of the basin in the studied area is drawn by using the ArcGIS program in the metric projection system. Monthly monitoring of the static water table (groundwater level fluctuation) of 24 wells in the basin is performed by using an electrical sounder over a one-year period in collaboration with the groundwater directorate team.

Data on groundwater fluctuation were collected from monitoring wells by special teams from Erbil's directorate of groundwater. Since 2001, the data has been collected on a regular basis. The teams of pumping tests in Erbil's groundwater directorate and the private sector have conducted numerous pumping tests. The tests were carried out using various tools and methods over a variety of time periods. Turbines and electrical submersible pumps were employed (Figure 2.2).

Figure 2.2. Measuring the groundwater level and evaluating the characteristics of the aquifer.

Raster and digital maps have been used in previous works, with special computer software used to create digital maps for previous studies.

2.3. Office Work

The programs that were running on the Microsoft Windows system were used. The following software and programs were used to perform calculations, modeling, mapping, statistics, and the creation of all curves and contour maps; Microsoft Excel 2010 has been used for data analysis, calculations, tables, correlation curves, lines, bars, and statistics; ArcGIS, Global Mapper 12.1, Map Info 10.5, and Google Earth have been used for designing maps of different purposes layers, and morphometric analyses; AQTESOLV software 2011 has been utilized for pumping tests, and Golden Software Surfer 21.1.158 has been used for contouring the lines.

3. GEOLOGICAL SETTING

The study area is mostly covered by Quaternary deposits, with a few outcrops of Miocene-Pliocene formations in the east, northeast, and west of the study area. The general geology of the study area is depicted in Figure 3.1. From oldest to youngest, the following is a description of the formations in the study area (Figure 3.2).

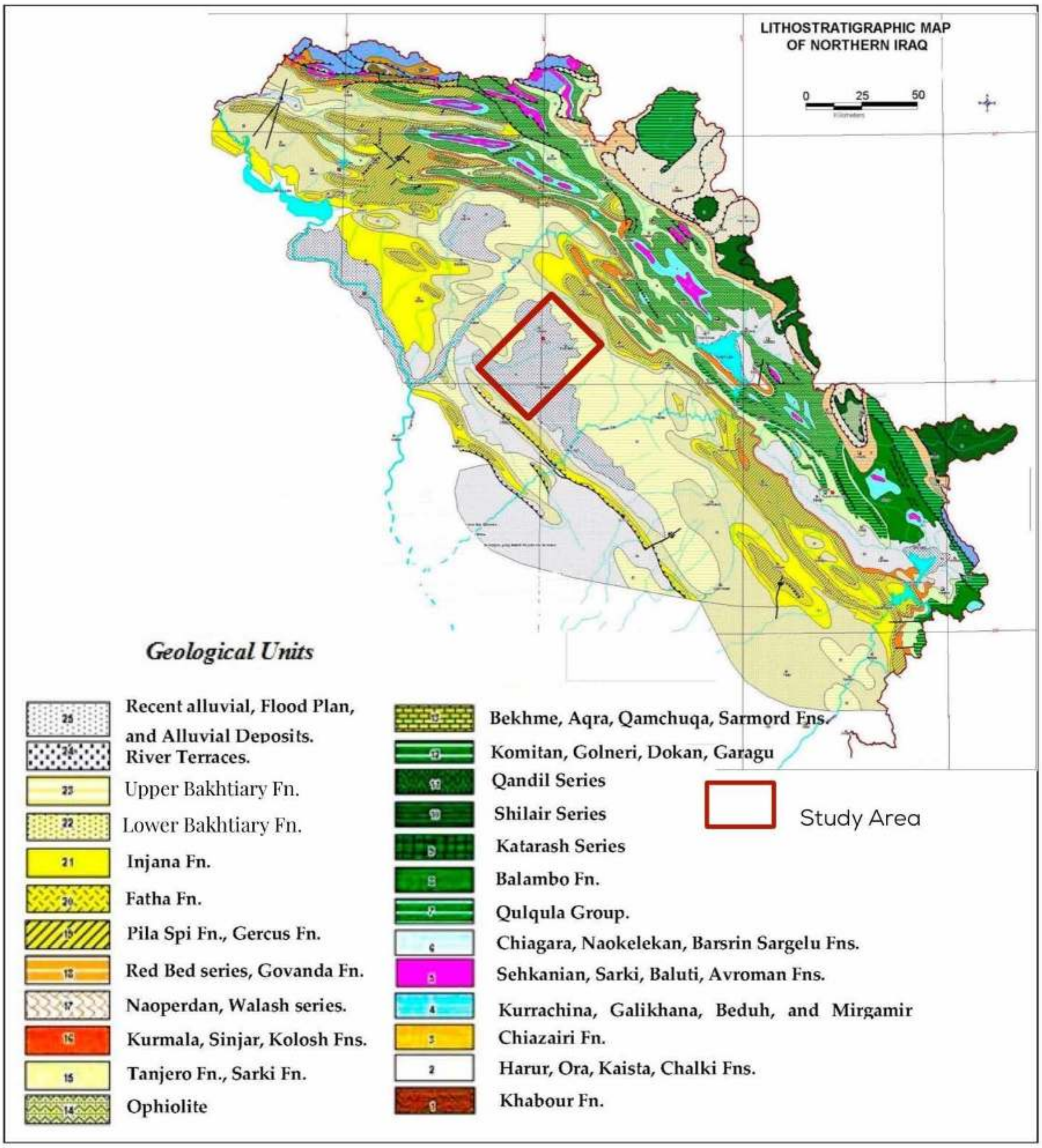

Figure 3.1. Geological map of Erbil central sub-basin (After Stevanovic, 2003).

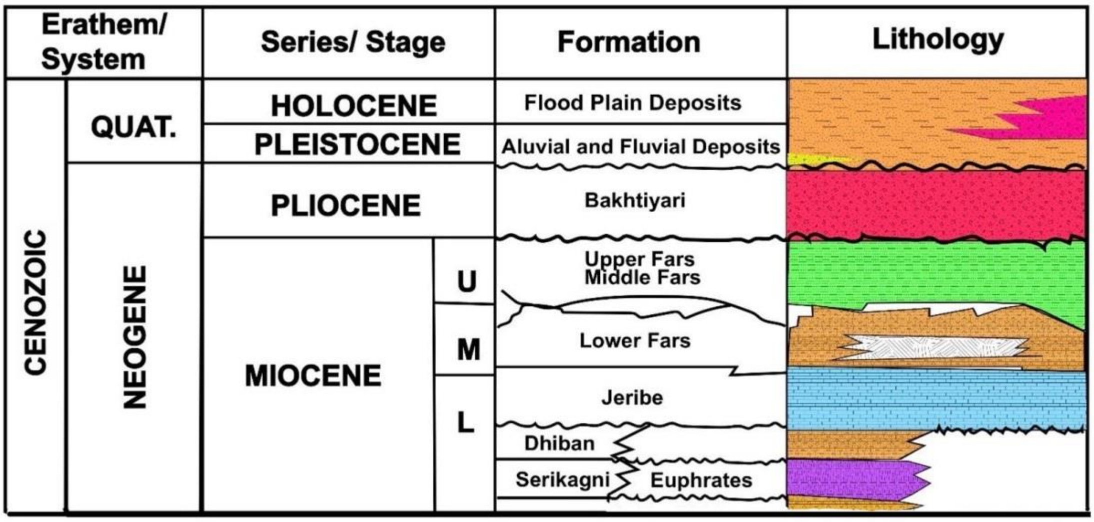

Figure 3.2. Geological units in the study area (after English et al., 2015).

3.1. Bakhtiary Formation (Late Miocene – Pleistocene)

Busk and Mayo were the first to describe the Iranian Bakhtiary Formation in 1918. The term was also well-known in Iraq. Because of fundamental variations and, to some extent, erosion, the thickness of the formation varies greatly. Maximum thicknesses can range from 2500 m to 3000 m (Al-Naqib, 1959). This formation was formed in a fluvial environment, in a rapidly sinking fore deep, and could be classified as typical Pliocene freshwater molasses (Mohamad, 1982).

Lower Bakhtiary Formation (=Mukdadyia Formation) (Late Miocene-Pliocene)

Northern Iraq has a large concentration of the formation. Its conglomerate can be followed all the way to southeast Turkey (Altinli, 1966). The formation's type region is widespread throughout southwest Iran, with the majority of them located in the Foothill zone (Buday and Jassim, 2006). The sediments were made up of fining upward cycles, molasses like conglomerate, pebbly sandstone, sandstone, siltstone, and lenses of mudstone, which formed rapidly sinking troughs (Internal Report, Directorate of Groundwater in Erbil, 2022). The eroded deposits are the result of relatively high surrounding mountains. The deposition system causes the thickness of the formation to varying from location to location. The thickness of the formation varies both laterally and vertically. The thickness of the Lower Bakhtiari Formation beneath the study area is 1829 m and it is 2000 m to 3000 m in the south of Erbil plain (Haddad, 1975; Hassan, 1981).

Upper Bakhtiary Formation (=Bai Hassan Formation) (Pliocene-Pleistocene)

The formation is primarily composed of, gravel, sandstone, claystone, and siltstone, as well as coarse and thick fluviatile lacustrine conglomerates produced by erosion of rising mountain ranges (Internal Report, Directorate of Groundwater in Erbil, 2022). Sediments of alluvium, diluvial, and eluvial origin deposited during the Pleistocene and Holocene epochs cover older rocks in most basins (Markovich and Stevanovich, 2004).

3.2. Quaternary Deposits (Pleistocene - Holocene)

According to Buday and Jassim (2006), the study area contains two types of Quaternary deposits; Pleistocene polygenetic deposits (silty and clay soils) and Holocene slope deposits (rock fragments with fine classics). The interior sections of the synclines are filled with polygenetic synclinal fill, which is composed of Quaternary sediments. Quaternary deposits cover the majority of the study area forming the Erbil Basin's most important aquifers (Figure 3.1). The Quaternary deposit aquifers are yielding from the majority of the good productive wells in the study area up to 300 m in depth (Figure 3.1). Quaternary deposits are poorly sorted, containing a wide range of grain sizes from pebbles to clays with varying textures; the most prominent textures are gravel, clay, mixed sand, silt, silty clay, etc, forming beds and lenses of varying thicknesses and horizontal extensions (Internal Report, Directorate of Groundwater in Erbil, 2022). Due to similar lithology and the lack of fossils, as well as the lack of a distinct clear key bed, distinguishing Quaternary deposits from the underlying Lower Bakhtiary Formation deposits is extremely difficult (Markovich and Stevanovich, 2004). In the study area, the thickness of the Quaternary deposits that had filled the Erbil Basin trough is unknown. According to Sissakian and Yukhana (1978), the Quaternary deposits are divided into slop deposits, river terrace, polygenic deposits and flood plain deposits.

Slop Deposits

Clay, silt, sand, and rock fragments from the Pleistocene and Holocene epochs make up the slope deposit. This type of deposit covers the majority of the study area.

River Terrace

These terraces were formed as a result of Pleistocene climatic oscillations in which periods of vertical river erosion alternated with periods of horizontal erosion. River terrace is consisting the aggradations rock fragments, limestone fragments, gravel (silica), and a small amount of igneous and metamorphic rock fragments (Jassim and Goff, 2006). This deposit has covered some of the research area.

Polygenic Deposits

It dates from the Pleistocene to the Holocene, and the polygenic deposit contains clay, silt, gypsum, sand, and gravel.

Flood Plain Deposits

The sediments are the result of river erosion during flood events. They're made up mostly of clay, silt, and sand, with a few fine pebbles and rock fragments thrown in for good measure. This deposit is Holocene in age (Sissakian and Yukhana, 1978).

3.3. Tectonics

The Zagros Belt in northern Iraq is a geologically recent Tertiary orogeny with a previous tectonic history of obduction-subduction (Numan, 1997; Jassim and Goff, 2006). The tectonic activity along the Zagros Belt has been ongoing for a long time, beginning in the Late Cretaceous, however, the final geometry developed during the Miocene-Pliocene period (Numan, 1997). The collision of the Arabian and Eurasian plates generated the Zagros Mountains, with the Arabian plate subducting beneath the Eurasian plate until it reached a collisional stage (Jassim and Goff, 2006). This collision resulted in the formation of a fold-thrust belt. The stable shelf of the Zagros orogeny in the north and northeastern Iraq has a shallow sedimentary layer with no substantial folding, whereas the unstable shelf has a thick and folded sedimentary cover with increased folding toward the northeast (Al-Juboury, 2012) (Figure 3.3). The unstable shelf is organized into four NW-SE striking tectonic elements: the Foothill Zone (Low Folded Zone), the High Folded Zone, the Imbricate Zone, and the Zagros Suture Zone (Numan, 1997; Jassim and Goff, 2006).

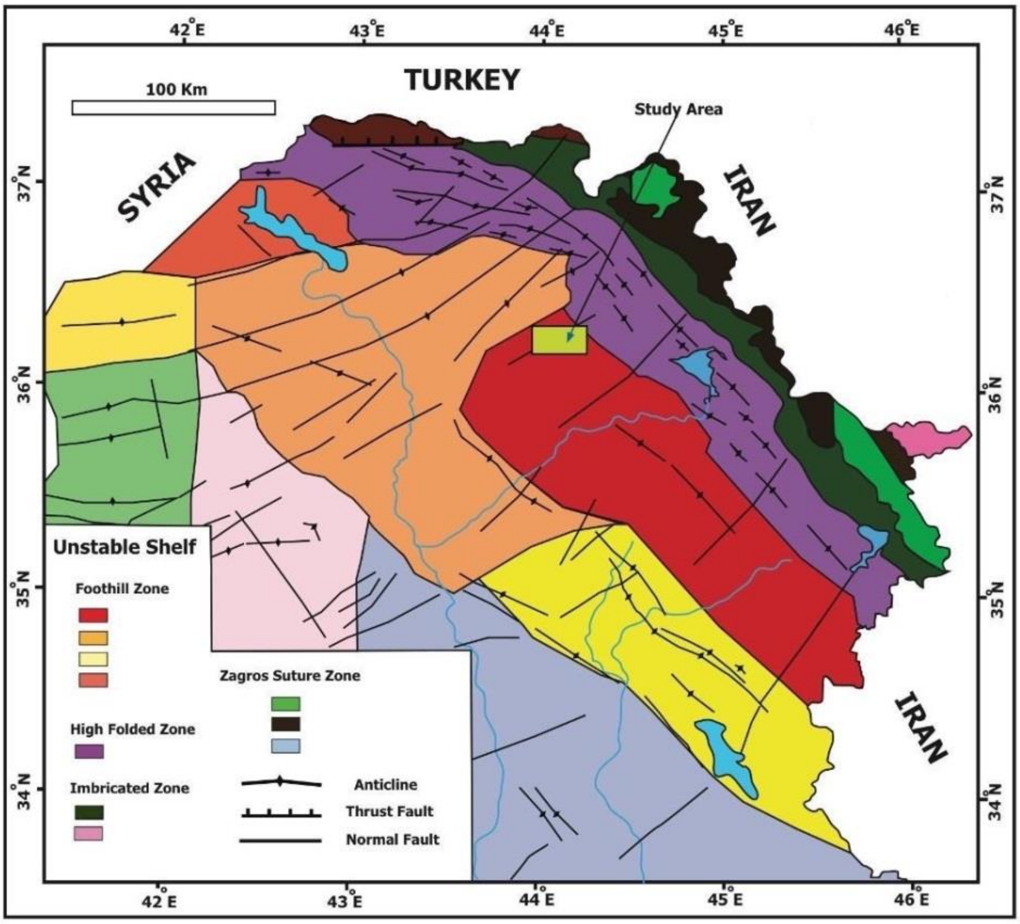

Figure 3.3. Tectonic zones and structural elements of the unstable shelf units (modified from Jassim and Goff, 2006)

The Erbil Basin is located in Northern Iraq's Low Folded Zone (Buday, 1980), defined the Low Folded Zone as a tectonic unit with low tectonic activity. Open folds with wavelengths ranging from 5 to 10 km dominate anticlines and narrow synclines. The Erbil basin is divided into three sub-basins (northern, central, and southern) (Bapeer et al., 2010). The Erbil Basin is deepening to the southeast, where antiforms and synforms are disappearing and formation thicknesses are increasing. To the north, the basin grows shallower, with more antiforms and synforms, as well as increased topography and tectonic activity. Topography changes when tectonic activity rises.

4. CLIMATE

The hydrologic cycle and water balance, both surface and subsurface, are controlled by climate elements, which are very important in hydrogeological studies. Precipitation, which is the source of all surface and subsurface water on continents, is the most important element of climate for water availability. Evaporation and evapotranspiration, on the other hand, are the most important factors in lowering water levels. All climate elements can have negative or positive effects on one another, or a combination (of positive and negative) can occur in some cases. The astronomic location, the location according to continents and seas and oceans, topography, air depressions, and air masses, according to Naqshbandi (2008), are the major factors controlling the climate of the north Iraq region. The major air masses that influence the climate are continental polar air masses, marine polar air masses, continental tropical air masses, and marine tropical air masses. The climate of the studied area belongs to the semi-arid climate region (Qurtas, 2013), and this type of climate is known for annual precipitation of less than 500 mm in the study area (Figure 4.1). The air temperatures are higher than in the northern and northeastern parts of the study area, and snowfall is uncommon. The climate is classified as continental (Rasul, 2004), and it is known for its hot summers and cold rainy winters The climate type is (the steppe climate region) (Haddad and Mahmud, 2011; Rasul, 2004) and (subtropical hot semiarid region) (Haddad and Mahmud, 2011).

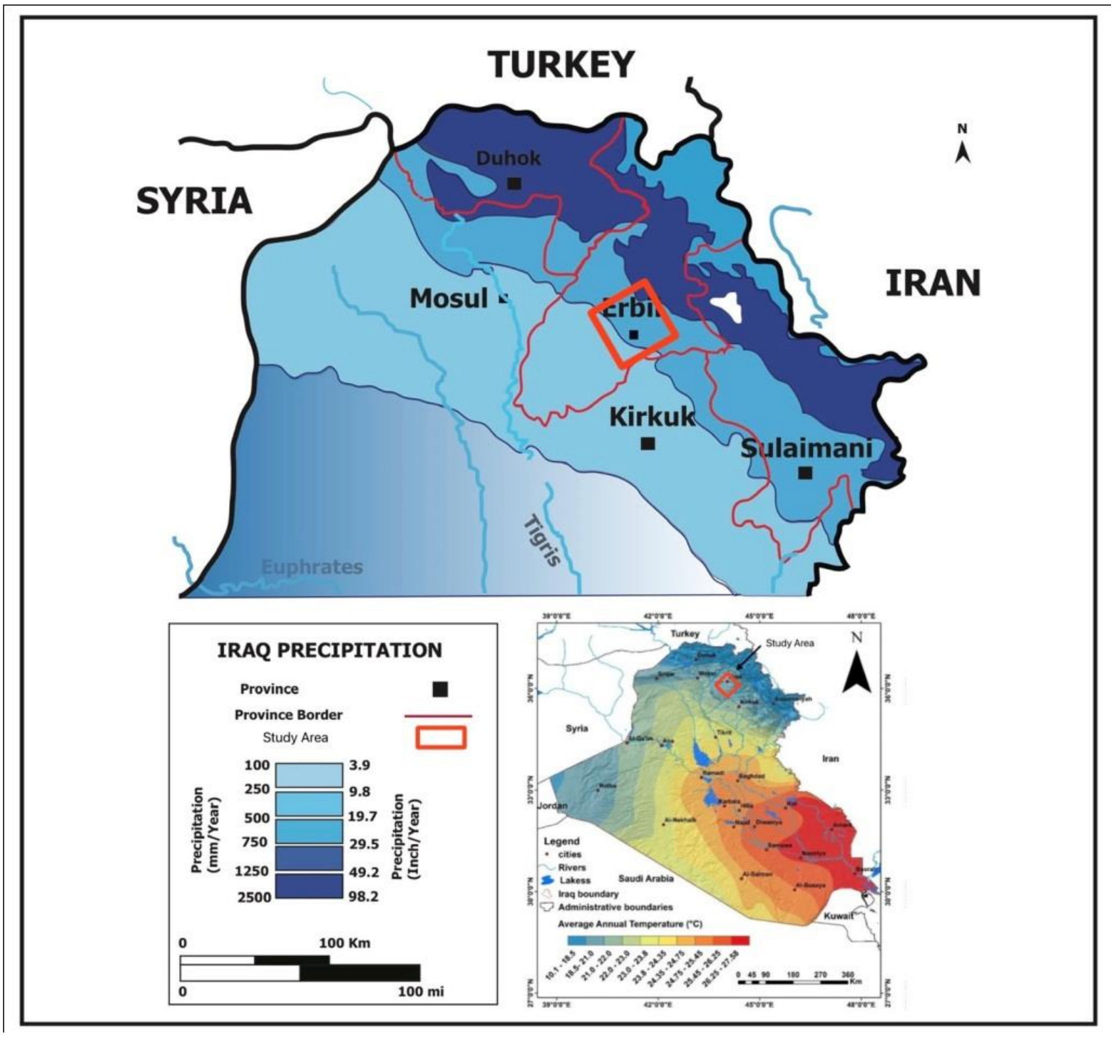

Figure 4.1. Spatial distribution of rainfall in the Erbil city (Hameed, 2013).

It was concluded that the Qushtapa area (south of the study area) is on the verge of desertification as a result of climate change and human activities, which are negatively affecting the physical characteristics of the soil and the wildlife in the area. The effects of global warming in the Erbil were reported. Reduced annual precipitation, rising average monthly temperature, changing current precipitation patterns (especially in low-rainfall areas), increasing the speed and amount of evaporation and evapotranspiration, and many other negative effects on plants and soil were among his key conclusions and predictions for this study. Precipitation data were collected from the Erbil meteorological station between 2001 to 2021. The regular and continuous recording of precipitation, surface temperature, relative humidity, evaporation, and other weather elements began in Erbil and was later followed by the installation of a meteorological station.

4.1. Climatic Element

4.1.1. Water Availability Elements

The most important characteristics of water availability are rainfall and relative humidity, as well as resources to limit climate change and water surplus.

Precipitation

According to the recorded data (General Directorate Of Meteorology and Seismology, 2022), the annual precipitation is changing from one year to another, it is also true for the monthly and daily precipitations which shows the highest annual precipitation from 2001 to 2021 was 733.6 mm in the year 2018 the lowest is 196.2 mm for the year 2021, and the average for the period is 392.5 mm (Figure 4.2). The whole period has two cycles. In the first cycle from 2001 to 2011, the highest is 514.6 mm in the year 2006, the lowest is 343 mm for the year 2011, and the average is 367.5 mm. In the second cycle, 2012 to 2021 the highest is 733.6 mm in the year 2018, the lowest is 196.2 mm in the year 2021, and the average is 420 mm. The highest monthly precipitation in the period 2001 to 2021 is 220 mm in March 2019.

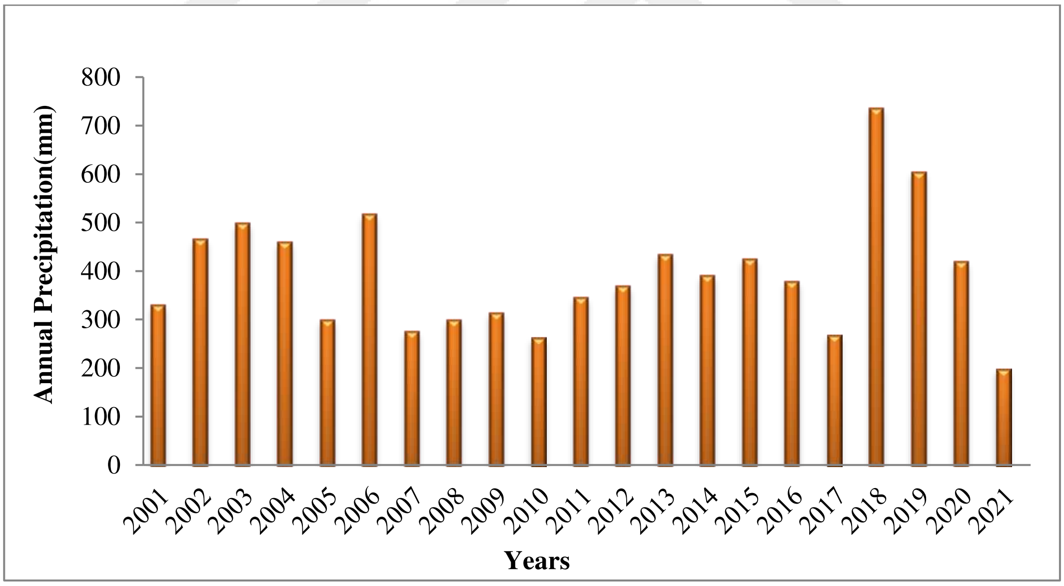

Figure 4.2. Annual precipitation in Erbil 2001 to 2021 (data collected from Erbil Meteorological station)

The maximum average monthly rainfall for the period from 2001 to 2021 is 69.5 mm in December in the study area (Table 6.1; Table 4.1 and Figure 4.3). The lowest rainfalls during this period are measured in July and August (no rainfall). The six months of November, December, January, February, March, and April are the rainy months, accounting for about 92% of the total precipitation in the year. However, the June, July, August, and September are almost dry months.

Table 4.1. Mean monthly precipitation (mm) in Erbil from 2001 to 2021(data were collected from Erbil meteorological station)

precipitation(mm)	Months											
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.
Mean	20.67	38.59	69.50	67.19	62.00	70.40	45.59	14.56	1.32	0.07	0.03	2.89
Max	89.60	132.9	187.80	174.40	189.00	220.10	123.50	74.60	9.10	1.30	1.00	32.60
Min	0.20	0.00	8.90	1.60	8.20	6.40	0.30	1.30	0.00	0.00	0.00	0.00

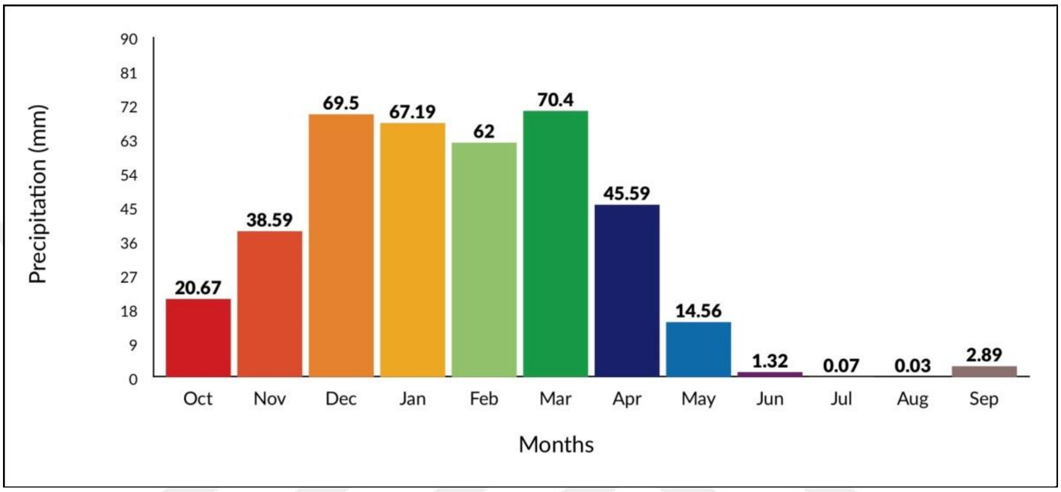

Figure 4.3. The average monthly precipitation of Erbil for the period between 2001 and 2021

Relative Humidity

The relative humidity is defined as the ratio of actual vapor pressure to saturated vapor pressure. It is a measure of how much moisture an air mass has and is connected to temperature and evaporation in reverse. The relative humidity of an air mass is usually given as a percentage (Dingman, 2002).

$$RH\% = e_a/e_s * 100 \quad (4.1)$$

$$e_s = 0.611 * \exp(17.3*T/T+237.3) \quad (4.2)$$

Rh%: Relative humidity of air mass percent (dimensionless)

e_a: Actual vapor pressure (kPa)

e_s: Saturation vapor pressure (kPa)

T: Temperature (°C)

Calculating relative humidity tells how much moisture is in an air mass. Relative humidity values greater than 80% indicate humid conditions that are expected to be below evaporation rates. In contrast, if it is less than 60%, it indicates a dry condition with high evaporation.

According to the average monthly relative humidity data collected at the Erbil meteorological station, only the three months of December, January, and February in the study area are humid, two months of November and March are intermediate (changing from humid to dry depending on precipitation and temperature throughout the year), and the remaining seven months April, May, June, July, August, September, and October are dry.

The most humid month in Erbil was January, and the driest was July (Table 4.2; Figure 4.4; Appendix 1). The highest average monthly relative humidity in the period from 2001 to 2021 in Erbil station was 83% in January 2003, and the driest was 22% in July 2005.

Table 4.2. Mean monthly relative humidity (%) for the period between 2001 and 2021 in Erbil.

Relative humidity %	Months											
	Oct.	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May.**	**Jun.**	**Jul.**	**Aug.**	**Sep.**
Mean	45.00	59.72	67.98	71.68	67.48	60.04	53.63	39.93	29.85	27.20	28.96	33.49
Max	63.00	73.60	82.10	83.00	78.90	74.40	71.30	55.60	39.10	34.30	35.10	53.00
Min	34.50	45.20	53.80	59. 50	50.00	35.00	26.00	23.00	22.00	22.00	24.60	24.50

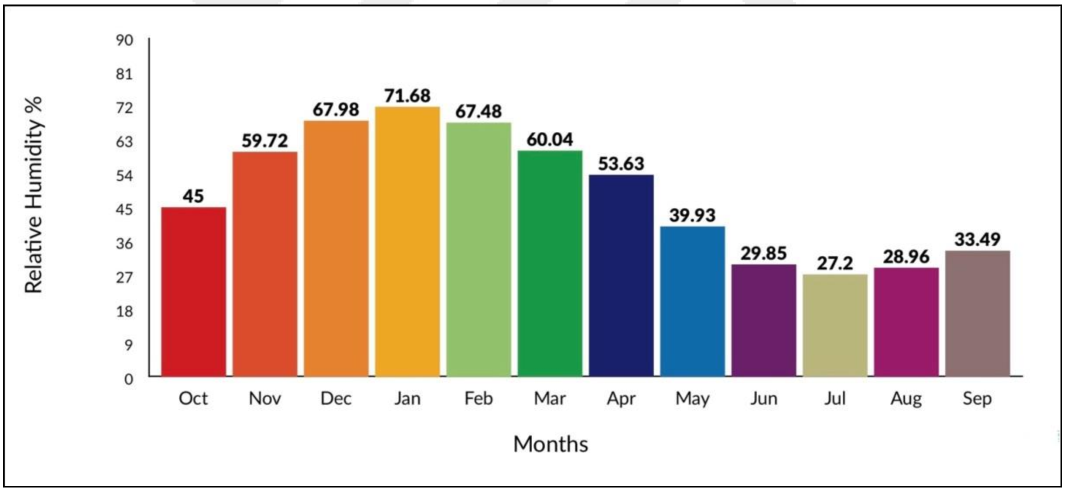

Figure 4.4. The average monthly relative humidity for the period between 2001 and 2021 in Erbil.

4.1.2. Water Losses Elements

Temperature

Temperature is the most important weather and climate element because it influences all other weather and climate elements and phenomena, both directly and indirectly (Naqshbandi, 2008). Topography, sunshine duration, latitude location, and other land and plant factors all have an impact on air temperature. The rhythm of a year's average monthly temperature is almost identical across years. In January 2008, the lowest average temperature recorded in Erbil meteorological station between 2001 and 2021 was 5.95 °C. In August 2006, the maximum average temperature for the same period was 36.6 °C. The average temperature during this time was 21.98 °C.

The average annual temperature is showing that the temperature is rising (i. e. the climate is warming in the area) (Figure 4.5; Appendix 2).

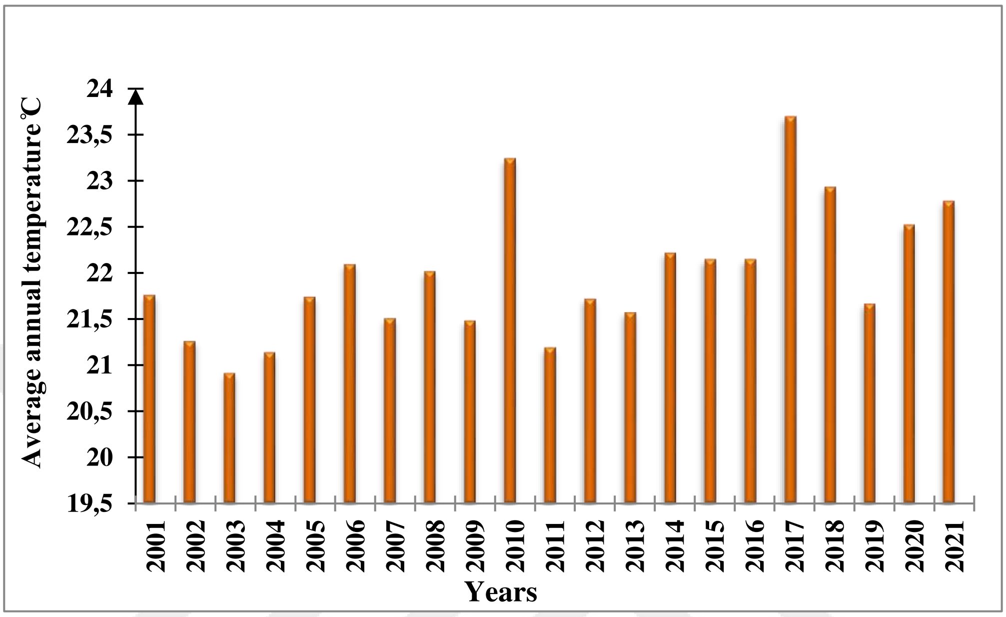

Figure 4.5. Average annual temperature for the period 2001 to 2021 in Erbil.

The coldest month according to averages of (mean, maximum, and minimum) was January, and the hottest was July; (Table 4.3; Figure 4.6).

Table 4.3. Mean monthly temperature (°C) of Erbil during 2001 to 2021 years (data was collected from Erbil meteorological station).

Temperature °C	Months											
	Oct.	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May.**	**Jun.**	**Jul.**	**Aug.**	**Sep.**
Mean	24.36	15.88	10.52	8.97	10.76	14.97	19.59	26.54	32.09	35.02	34.70	30.04
Max	25.80	19.27	13.80	11.86	12.85	17.60	28.29	29.56	34.21	36.58	36.60	32.70
Min	22.35	12.55	6.00	5.950	8.55	11.20	15.72	24.45	30.70	33.10	32.50	27.31

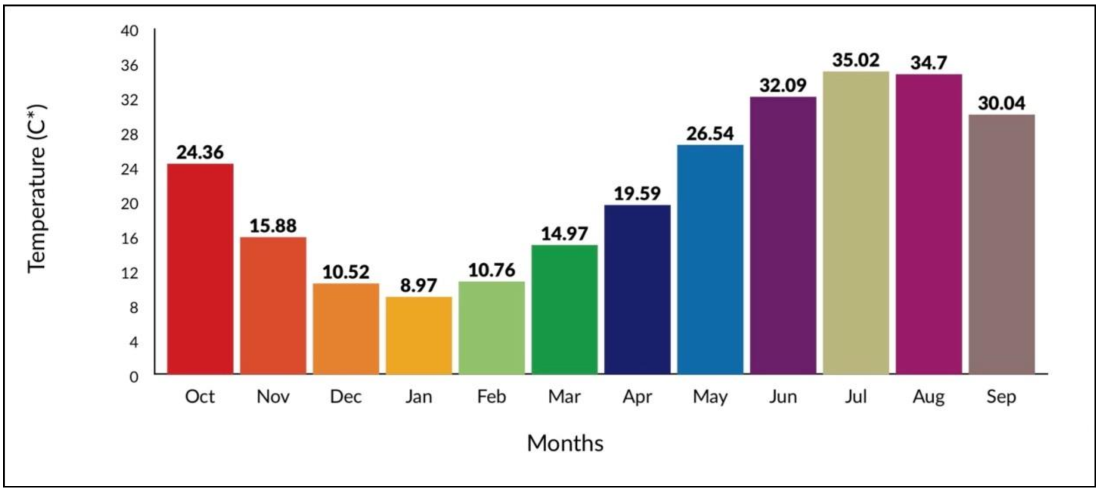

Figure 4.6. Average monthly temperature for the period between 2001 and 2021 in Erbil.

Sun Shine Duration

The average monthly maximum sunshine duration is 11.86 hours/day in July, while the average monthly minimum duration is 4.88 hours/day in January. From 2001 to 2021, the mean annual sunshine duration was 8.2 hours/day (Table 4.4; Figure 4.7; Appendix 3).

Table 4.4. Mean monthly sunshine (h/day) duration in Erbil during period from 2001 to 2021 (data were collected from Erbil meteorological station).

Sunshine (h)	Months											
	Oct.	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May.**	**Jun.**	**Jul.**	**Aug.**	**Sep.**
P%= (h)	7.76	6.42	5.32	4.88	5.61	6.59	7.55	9.42	11.67	11.85	11.22	10.18

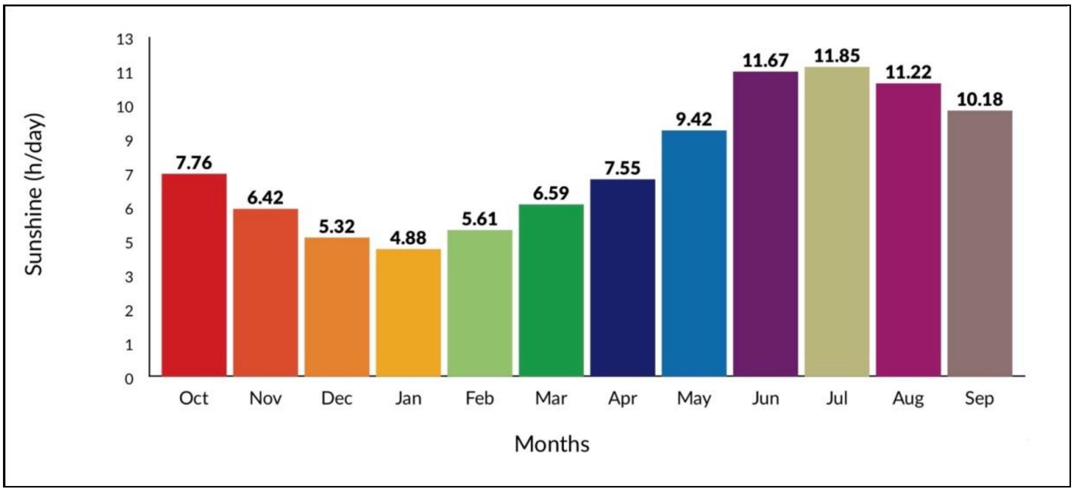

Figure 4.7. Average monthly sunshine duration duration in Erbil during period from 2001 to 2021 (data were collected from Erbil meteorological station).

Evaporation from class (A) pan

Measurement of evaporation from class (A) pan is a method for calculating free water evaporation. The change in the water level in the pan is used to calculate evaporation. The pan coefficient is the ratio of lake evaporation to pan evaporation; its annual average is usually around 0.7, but this value varies with the seasons due to changes in heat storage. This equation was developed by (Kohler et al., 1955), to calculate the daily free water evaporation based on pan evaporation and air temperature:

$$E_{fw} = 0.7 * [E_{pan} \pm 0.064 * P * a_{pan} * (0.37 + 0.00255 * v_{pan}) * (Tspan * Ta|^{288} \quad (4.3)$$

E_{fw}:. Free water evaporation (mm/day)

E_{pan}: pan evaporation (mm/day)

P: Atmospheric pressure (KPa)

a_{pan}: Portion of energy exchanged through the sides of the pan.

v_{pan}: Average wind speed at a height of 15 cm above the pan (km/day)

T_{span}: Water surface temperature in the pan (°C)

T_a: Air temperature (°C)

The measurement of monthly average evaporation by using of the Class-A pan in Erbil meteorological station (from 2001 to 2021) is given in (Table 4.5 and Appendix 4; and shown on Figure 4.8.

Table 4.5. Mean monthly evaporation (mm) measurements with a Class-A pan in Erbil during period from 2001 to 2021 (data were collected from Erbil meteorological station)

Evaporation (mm)	Months											
	Oct.	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May.**	**Jun.**	**Jul.**	**Aug.**	**Sep.**
Mean	6.40	3.16	1.87	1.70	2.48	4.01	5.78	9.39	12.76	13.60	12.89	9.72
Max	9.70	4.80	2.60	2.80	4.30	6.50	10.20	12.60	15.60	17.20	18.50	12.80
Min	4.40	2.20	1.20	1.10	1.70	2.20	4.10	7.20	10.30	10.60	9.60	8.10

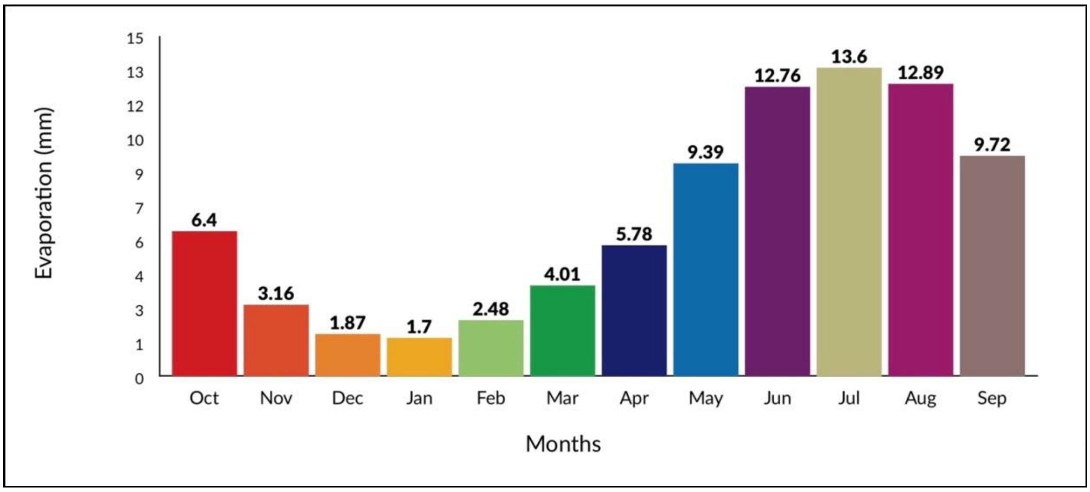

Figure 4.8. Average monthly evaporation class (A) pan in Erbil during period from 2001 to 2021 (data were collected from Erbil meteorological station).

4.1.3. Water Balance Technique

There are various methods for determining water balance, the majority of which rely on available meteorological data. The potential and actual evapotranspiration of the studied area were calculated using hydro-meteorological data from the Erbil metrological station, and the calculated value was used to determine the water surplus and water deficit periods. The approach can predict potential groundwater recharge but not aquifer yield when rainfall data is utilized to compute runoff (Aqrawi, 2003). As a result, the water balance technique is a simple and quick method to implement (Shwani,2008). Three different methods were chosen in the present study to determine the most suitable method for the basin to determine evapotranspiration, water surplus and water deficit in the studied area. These methods are Thorntwaite, Braney- Criddle and Kharrufa methods.

Evapotranspiration (ET)

The water loss will occur if there is never a lack of water in the soil for vegetation use (Viessman and Lewis, 2012). Sublimation, or liquid precipitation that reaches the earth's surface, is transformed into water vapor and returned to the atmosphere by evaporation. Plants lose water through transpiration. Because it is often difficult to distinguish between transpiration from plants and evaporation from a water surface, they are often grouped together under the umbrella term evapotranspiration, or ET (Weight, 2004). The maximum amount of water that would be removed from the surface by evapotranspiration if there was enough water in the soil to meet demand is referred to as potential evapotranspiration (PET) (Hamill and Bill, 1986). This technique was used by several Iraqi researchers, including Al Kubaise (1996); Hassan (1998); Chnaray (2003); Aqrawi (2003); Shwani (2008) and Dara (2011). Depending on the calculated available hydro-climatic data for the studied area, potential evapotranspiration can be determined using a variety of techniques.

Thornthwaite Method

Climate conditions, according to Thornthwaite and Wilm (1944), control the amount of water lost due to evaporation from the soil surface covered by vegetation. The annual air temperature plus the average monthly air temperature for that month are used to calculate the potential evaporation for that month (Serrano, 1997). Many researchers have used this method (Alkubaisy, 1996; Hassan, 1998; Chnaray, 2003). The equation is written as follows:

$$PET = L_a\,16\,(10*T / J)^a \qquad \text{mm/month} \tag{4.4}$$

$$J = \sum j \qquad \text{for each month} \tag{4.5}$$

$$j = (t/5)^{1.154}$$

$$a = (675 \times 10^{-9})J^3 - (771 \times 10^{-7})J^2 + (179 \times 10^{-4})J + 0.492 \tag{4.6}$$

where: PET : Potential evapotranspiration in mm

L_a : Monthly correction constant function of latitude.

j : Monthly temperature parameter

J : Annual heat index (°C)

T : Mean monthly temperature (°C)

The PET values for the Erbil basin were calculated using the Thornthwaite method over time 2001 to 2021 (Table 4.6), which depicts the water deficit and surplus, as shown in (Figure 4.9).

Table 4.6. Potential evapotranspiration values calculated by Thornthwaite method for the period 2001 to 2021. in Erbil during period from 2001 to 2021 (data were collected from Erbil meteorological station).

Months	T °C	i=t/5	j=(t/5)1.514	J	10t/J	a	La	L F	PET
Oct.	24.36	4.87	10.99	120.96	2.01	2.72	0.97	107.42	104.20
Nov.	15.88	3.18	5.75	120.96	1.31	2.72	0.86	33.55	28.85
Dec.	10.54	2.11	3.09	120.96	0.87	2.72	0.84	11.00	9.24
Jan.	8.98	1.80	2.43	120.96	0.74	2.72	0.87	7.12	6.19
Feb.	10.73	2.15	3.18	120.96	0.89	2.72	0.85	11.55	9.82
Mar.	14.97	2.99	5.26	120.96	1.24	2.72	1.03	28.57	29.43
Apr.	19.89	3.98	8.09	120.96	1.64	2.72	1.10	61.89	68.08
May.	26.55	5.31	12.53	120.96	2.19	2.72	1.21	135.77	164.28
Jun.	32.09	6.42	16.69	120.96	2.65	2.72	1.22	227.33	277.34
Jul.	35.03	7.01	19.06	120.96	2.90	2.72	1.24	288.54	357.79
Aug.	34.70	6.94	18.79	120.96	2.87	2.72	1.16	281.21	326.20
Sep.	30.05	6.01	15.11	120.96	2.48	2.72	1.03	190.14	195.84

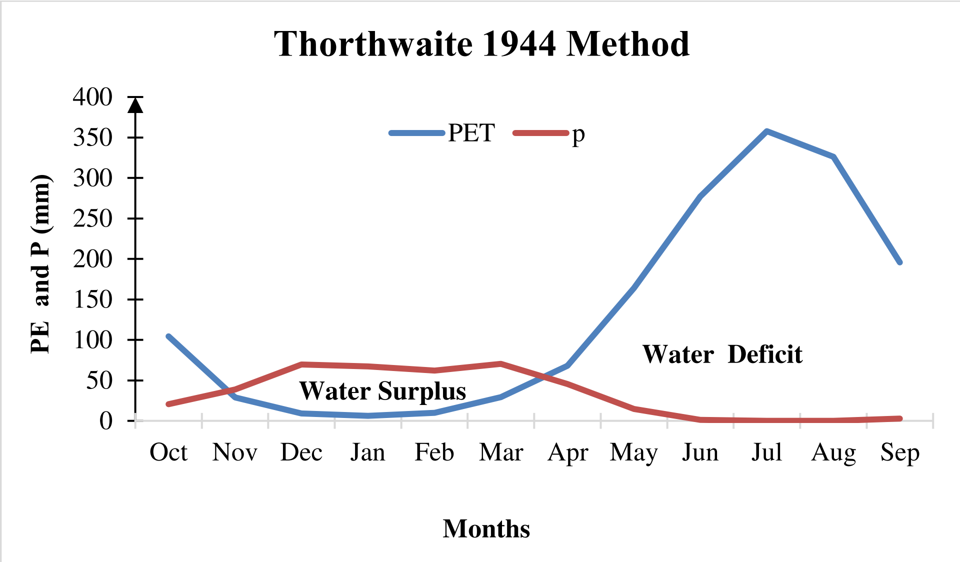

Figure 4.9. Mean monthly water surplus and water deficit calculated by Thornthwaite method.

Blaney-Criddle Method

The Blaney-Criddle method can be used if the monthly mean air temperature is the only data available. This method is classified as a temperature method. The equation Blaney-Criddle (1962) is as follows:

$$PET = K*P\ (0.457*Ta + 8.13) \qquad (4.7)$$

where:

K: Crop Coefficient or correction factor its value can be found as follow:

$$K:\ (0.0311 * Ta + 0.24) \qquad \text{(Hassan, 1998)} \qquad (4.8)$$

PET: Potential Evapotranspiration

P: Monthly percentage of day light hours in the year

Ta: Mean monthly air temperature (°C)

Table 4.7, shows that the PET value calculated by this method is higher than that calculated by the Thornthwaite method, and Figure 4.10, shows the water deficit and surplus calculated by this method in the Erbil basin.

Table 4.7. Potential evapotranspiration values calculated by Blaney-Criddle method for the period 2001 to 2021. in Erbil during period from 2001 to 2021 (data were collected from Erbil meteorological station).

Month	T °C	p	K	PET
Oct.	24.36	7.76	0.99	148.54
Nov.	15.88	6.42	0.73	72.33
Dec.	10.54	5.32	0.56	38.66
Jan.	8.98	4.88	0.51	30.51
Feb.	10.73	5.61	0.57	41.78
Mar.	14.97	6.59	0.70	69.26
Apr.	19.89	7.55	0.85	110.89
May.	26.55	9.42	1.06	203.12
Jun.	32.09	11.67	1.23	328.58
Jul.	35.03	11.86	1.32	379.54
Aug.	34.70	11.22	1.31	354.10
Sep.	30.05	10.19	1.17	261.73

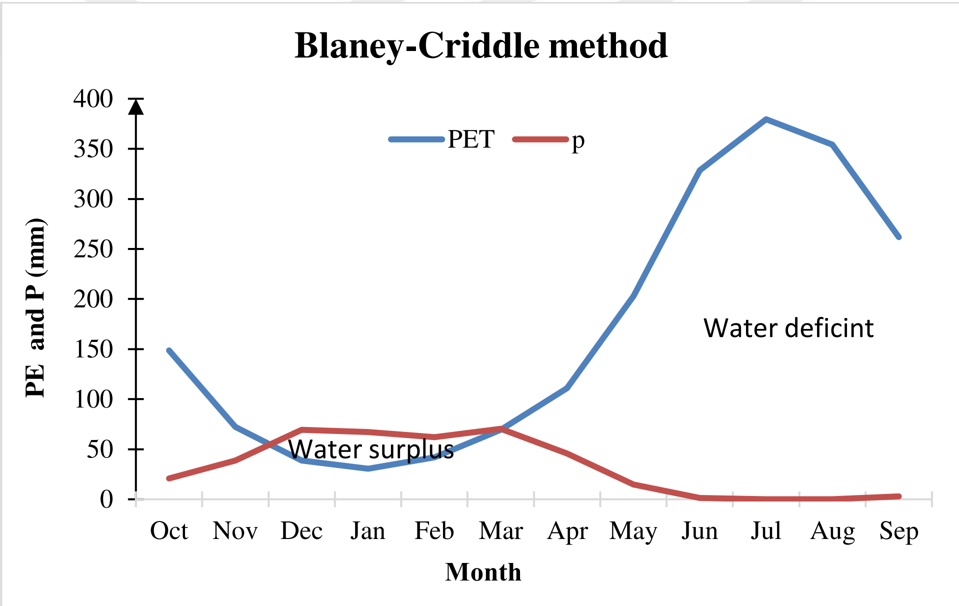

Figure 4.10. Mean monthly water surplus and water deficit calculated by Blany-Criddle method.

Kharrufa Method

For calculating PET values Kharrufa (1985), devised a simple formula. Based on the relationship between temperature and sunshine duration, various researchers adopted this strategy in Iraq which is considered to be the most appropriate method for the Iraq climate (Hassan, 1998; Chnaray, 2003; Shwany, 2008; Dara, 2011; Masoud, 2013; Qurtas 2013). The formula is as follows:

$$PET / \rho = at^m \tag{4.9}$$

where:

t: Mean monthly temperature (°C)

ρ: The percent of sum of sun shine hours in each month to the sun shine hours of one year.

M: Constant (1.31)

a: Constant (0.33)

Table 4.8. shows that the PET values calculated by this method are similar to those calculated by the Blany-Criddle method for the various months. Still, they differ from those calculated by the Thornthwaite method. The former method used two parameters in the formulas. In contrast, the latter used only one climatic factor in the equation: the mean monthly temperature and a relative latitude correction factor Figure 4.11, depicts the water deficit and surplus calculated using this method in the Erbil basin.

Table 4.8. Potential evapotranspiration values calculated by Kharrufa method for the period 2001 to 2021. in Erbil during period from 2001 to 2021 (data were collected from Erbil meteorological station).

Month	T °C	P (h)	T^1.31	PET
Oct.	24.36	7.76	65.54	169.53
Nov.	15.88	6.42	37.42	80.07
Dec.	10.54	5.32	21.87	38.78
Jan.	8.98	4.88	17.73	28.84
Feb.	10.73	5.61	22.39	41.86
Mar.	14.97	6.59	34.63	76.07
Apr.	19.89	7.55	50.25	126.46
May.	26.55	9.42	73.37	230.38
Jun.	32.09	11.67	94.04	365.81
Jul.	35.03	11.86	105.4	417.03
Aug.	34.70	11.22	104.19	389.67
Sep.	30.05	10.19	86.29	293.09

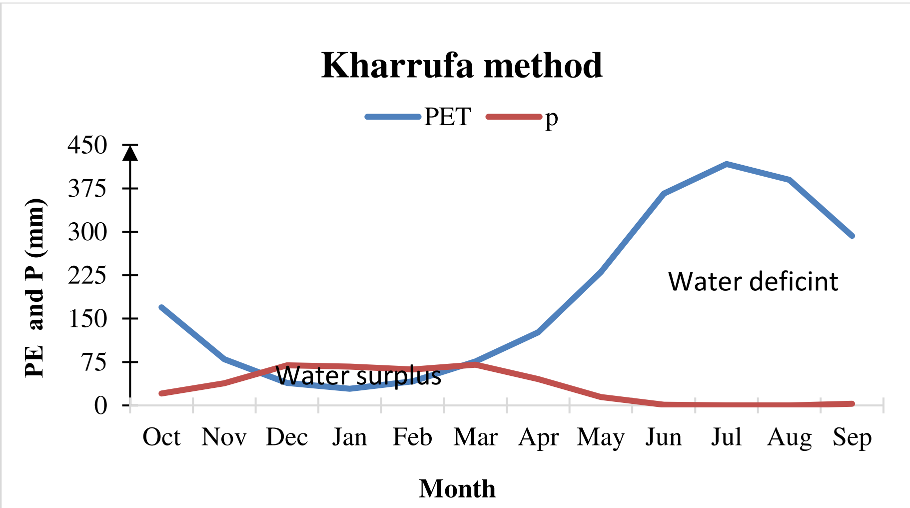

Figure 4.11. Mean monthly water surplus and water deficit calculated by Kharrufa method.

Water Surplus and Water Deficit

When precipitation exceeds potential evaporation over a period of time, there is an excess of water, whereas when potential evaporation exceeds precipitation, there is a water deficit.

WS = P PE ; P > PE

WD = PE P ; P < PE

where:

WS : Water Surplus

WD : Water Deficit

P : Rainfall

PE : Potential evapotranspiration

Real evaporation approaches its potential value when there is more water available, but when there is less water available, actual evapotranspiration (AET) equals precipitation (Hassan, 1998).

P > EP then PE = AET

P < EP then P = AET

Total runoff (Rs), groundwater recharge (recharge), and soil moisture are all included in the water surplus (irrigation). There is no evaporation from the groundwater in the Erbil Sub Basin because the groundwater table is so deep. As a result, either evaporation from the soil or plant consumption consumes soil moisture. The water balance equation is as follows:

P = Rs + I + AET (4.10)

Rs + I = WS

WS = P AET

where:

AET: Actual evapotranspiration

Rs: Surface runoff

I: Infiltration

In the Kharrufa method, the mean monthly potential evapotranspiration values were computed (Table 4.9). They were then used to calculate the mean monthly actual evapotranspiration and the mean monthly water surplus and deficit in the study area. From the beginning of March to the end of November, there is a clear water shortage because PET exceeds precipitation and, as a result, soil moisture utilization. Between the end of December and the end of February, precipitation exceeds PET, causing soil moisture to recover to capacity and the extra or excess water to become groundwater recharge and surface runoff.

Table 4.9. Water surplus and water deficit using values calculated by Kharrufa method.

Month	Monthly p (mm)	Monthly PET (mm)	Monthly AET (mm)	Monthly WS (mm)	Monthly WD (mm)
Oct.	20.67	169.53	20.67		148.86
Nov.	38.59	80.07	38.60		41.47
Dec.	69.52	38.78	38.78	30.72	
Jan.	67.20	28.84	28.84	38.36	
Feb.	62.02	41.86	41.86	20.14	
Mar.	70.39	76.07	70.39		5.67
Apr.	45.58	126.46	45.60		80.86
May.	14.57	230.38	14.57		215.81
Jun.	1.32	365.81	1.32		364.49
Jul.	0.07	417.03	0.07		416.96
Aug.	0.047	389.67	0.04		389.63
Sep.	2.89	293.09	2.89		290.20
Total	392.867	2257.59	303.63	89.22	1953.95

4.1.4. Surface Runoff

Surface runoff is calculated using the Soil Conservation System (SCS) method using rainfall data. The following is the empirical rainfall-runoff relationship:

$$Q = (P - 0.2\ S)^2 / P + 0.8\ S \qquad (4.11)$$

where:

Q: Runoff (mm) of depth

P: Monthly Rainfall (mm)

S: Retention including the initial abstraction [S=1000/CN – 10]

CN: Curve number.

When detailed data on soil and vegetation cover is available, this method is used. The method was developed from numerous rainfall and runoff records, as well as numerous soil and cover combinations (Table 4.10; Figure 4.12), shows how the SCS approach was implemented with four soil classes (hydrologic soil groups).

Table 4.10. Hydrologic soil groups based on infiltration rates (Maidment, 1993)

Group type	Infiltration rate cm/h	Runoff rate	Soil Description
A	≥ 0.76	Low	Sands or gravels
B	0.38 – 0.76	Moderate - Fine	Silt loam and loam
C	0.13 – 0.38	Fine - High	Sandy clay loam
D	0.0 – 0.13	High	Clay loam, silty clay loam, sandy clay, silty clay and clay

The soils of the Erbil Central sub-basin are of mixed type, with grain sizes ranging from fine clay to coarse sand (Khasback, 1973; Jassim, 1978), and the vegetation cover during the rainy season is wheat, with straight row cultivation being used for soil treatment, so the soil is classified as class A according to the classification proposed by this method (Table 4.10). As a result, the curve number for this soil condition is 65. The Erbil meteorological station's mean monthly precipitation values (records) were used to estimate (Rs) values from the standard graphs in Figure 4.12. as shown in Table 4.11.

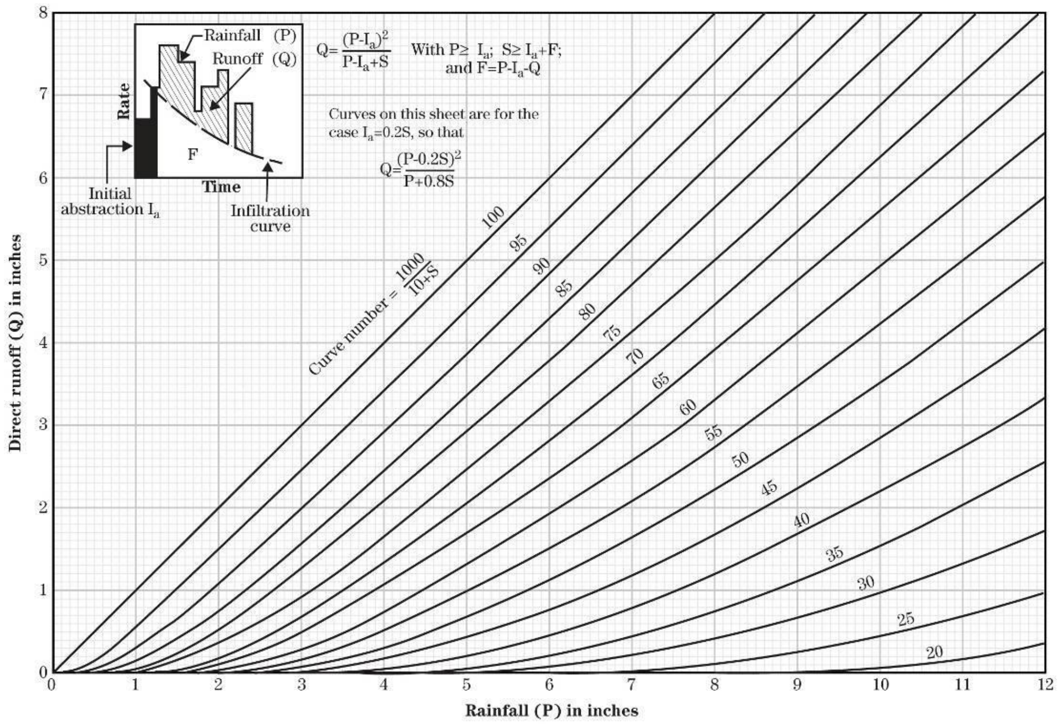

Figure 4.12. Nomograph for relationship of rainfall-surface runoff (after Evans, 1971)

Table 4.11. Runoff values calculated by Soil conservation system

Month	Monthly Pm (mm)	Rs (mm)
Oct	20.67	0
Nov	38.59	0
Dec	69.52	9.91
Jan	67.2	8.89
Feb	62.02	6.39
Mar	70.39	10.16
Apr	45.58	2.54
May	14.57	0
Jun	1.32	0
Jul	0.07	0
Aug	0.047	0
Sep	2.89	0
Total	392.867	37.85

5. RESULTS AND DISCUSSION

Pumping tests and water table monitoring are the most important methods for determining or calculating the hydraulic characteristics of aquifers. The quality of these data is extremely important, and it is determined by how the data were gathered, how long the test lasted, when it was tested, the purpose of the test, and anything else that affects the quality of the pumping test data. The same can be said for water table monitoring. Calculating and accurately identifying the hydrogeology of the study area is accomplished by identifying aquifer types and systems, as well as calculating hydraulic properties, which aid in the development of good and accurate models for the hydrogeology system of the formations in the study area. All of this helps to determine the balance between recharge and outflow, as well as future groundwater management forecasts.

The Erbil Basin, located south of the Pirmam mountain, is characterized by vast plains. It is characterized by the presence of dense sediments in the middle of the plain. The groundwater flows to the southwest towards the Greater Zab River and partly towards the Lesser Zab River in the southern part of the Erbil Basin. The geological and topographic characteristics of this area were critical in determining the discharge and recharge zones (Jassim and Goff, 2006). The Kapran sub-basin, the Central sub-basin, and the Bashtapa sub-basin are the three sub-basins that make up the Erbil Basin (Habib et al., 1990). This division was made using hydrogeological data from deep wells, previous groundwater studies, and water quality data (Ahmad, 2002). Minor surface and subsurface structures separate sub-basins. The Kirkuk structure - Awana anticline (Zurgazraw, the local name), forms the western and southwestern boundaries. It is an asymmetrical anticline, with the highest elevation in the study area in the southwest being 450 m and the dip of the west-east limb of the anticline being about 12°. The water divide between the Greater and Lesser Zab forms the southern boundary. The master plan of Erbil city covers a large portion of this area. The plan covers a wide range of sectors, including urban, industrial, transportation, irrigation, and fishing.

The Erbil Central sub-basin is one of the most important and promising hydrogeological zone for groundwater resources in the low-lying fold area (Figure 5.1).

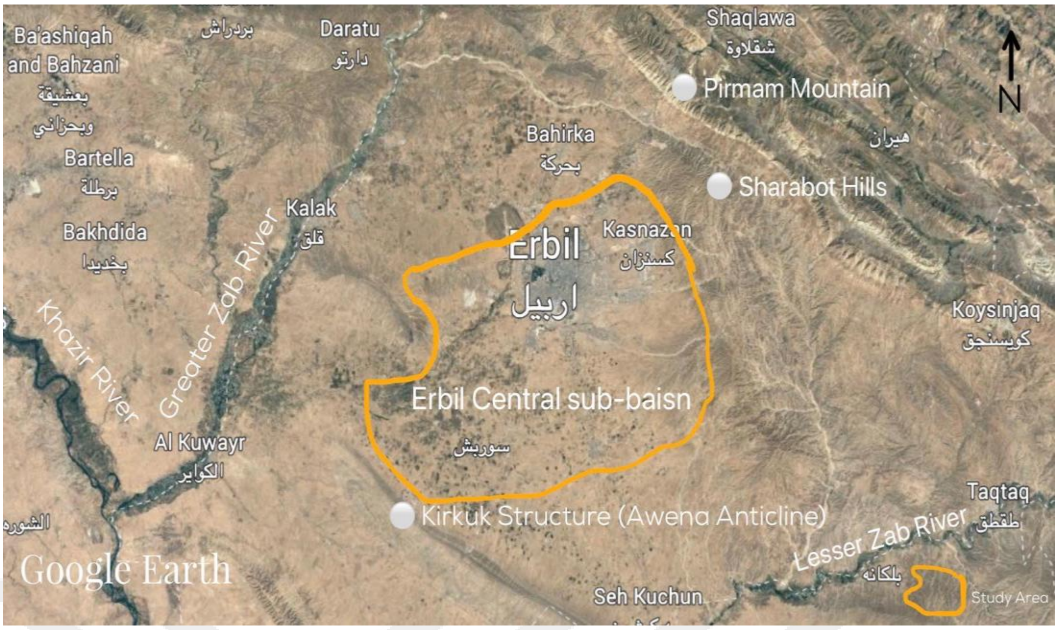

Figure 5.1. Location and boundary of Erbil Central sub-basin (Google Earth pro image)

5.1. Hydrogeology of the Erbil Central sub-basin

The area of this sub-basin is 1400 km^2. The Upper and Lower Bakhtiary Formations, as well as alluvium, are found in this sub-basin. The Quaternary deposits are made up of gravel, clay, mixed sand, silt, and silty clay. The Bakhtiary Formation's upper part is made up of gravel, sandstone, claystone, and siltstone, as well as coarse and thick fluviatile lacustrine conglomerates produced by erosion of rising mountain ranges. Some deep wells drilled in the Lower Bakhtiary Formation, on the other hand, are composed of thin beds of conglomerate, pebbly sandstone, sandstone, siltstone, and lenses of mudstone (Ahmad, 2002).

5.2. Aquifer limits and physical properties:

The majority of the semi-flat lowlands in the study area are made up of Quaternary deposits (alluvium and slope deposits), which have a complicated stratigraphic context and lithology diversity both laterally and vertically. A variety of forces influence its structural behavior, resulting in a variety of surface and subsurface structures.

The Erbil Central sub-basin is bounded by many surfaces and subsurface structures; the eastern part's boundary is the Sharabot hills, which suggested that the rise of the basement occurred due to a reverse fault there, and the water levels there are considered from the highest hydraulically the feeding zone (Gabib, 2000). The associated transverse rift zone, the boundary between the Kapran sub-basin and the Bashtapa sub-basin, is affected by the same shear stress that caused the transverse fault system, to bend potential groundwater lines like a V-shape, and flow in opposite directions. The structure of Kirkuk forms the basin's southwestern boundary, and its line runs northwest to south. The depth of producing wells varies between 250 to 450 m. The exploited depth of the aquifer where the production wells were penetrated is primarily the Quaternary deposits and the Upper and Lower Bakhtiary formations. The lack of a survey of detailed hydrogeological studies in the study area means that there isn't enough hydrogeological information about the aquifers below this depth. The bound strata (mudstones) and cohesive sediments of the Upper and Lower Bakhtiary formations, in general, make up the basin's minimal aquifer systems. However, due to the layers of soil and sedimentation in the formations, in which the confined layers do not persist for long distances but are overlapping and in between, it is suggested that the aquifers are not completely vertically isolated from the deep aquifers of the Fars formations. Another theory is that vertical groundwater movement occurs through deep fissures, which connect shallow and deep aquifers as well as aquifers and surface (Qurtas, 2013).

Aquifer properties

Twenty four wells were selected within the study area in the Erbil Central sub-basin. Approximately 12 of the selected wells penetrate alluvium, 8 wells penetrate alluvium and Bakhtiary Formation, and the remaining four wells penetrate the Bakhtiary Formation (Table 5.1; Figure 5.2).

Table 5.1. Information about 24 selected wells in Erbil Central sub-Basin (-. not determined).

No	Well Name	Static water level (m)	Dynamic water level (m)	Depth (m)	Producing Formation	Alluviam (m)	Upper Bakhtiary Formation (m)	Aquifer Condition	GPS Coordinate (UTM) X	GPS Coordinate (UTM) Y	Elevation (m)
W01	Qoritan Chukul	76.80	139.30	350.0	Alluvium	0.0-350.0	-	Unconfined	405405	3993247	317.0
W02	Tandura -1	77.20	110.00	350.0	Alluvium+Bakhtiary	0.0-70.0	70.0-350.0	Unconfined	395403	3993029	315.0
W03	Mastawa	77.60	89.00	250.0	Alluvium+Bakhtiary	0.0-85.0	85.0-250.0	Unconfined	393525	3989963	308.0
W04	Shekh Sherwan	72.90	84.00	205.0	Alluvium+Bakhtiary	0.0-50.0	50.0-205.0	Unconfined	385953	3989337	293.0
W05	Grd Azaban	79.50	131.00	280.0	Alluvium+Bakhtiary	0.0-60.0	60.0-280.0	Unconfined	394916	3985193	303.0
W06	Perdawood	69.70	94.50	302.0	Alluvium	0.0-302.0	-	Unconfined	403046	3986980	340.0
W07	Satoor-1	115.80	140.20	335.0	Lower Bakhtiary	-	0.0-335.0	Unconfined	391868	4004653	440.0
W08	Dugrdkan	96.30	103.80	220.0	Alluvium	0.0-220.0	-	Unconfined	405007	3981457	350.0
W09	Murtka Shahab	87.00	119.00	350.0	Alluvium	0.0-350.0	-	Unconfined	412718	3988467	408.0
W10	Bestanay gawra	86.08	207.20	298.0	Upper Bakhtiary	-	0.0-298.0	perched	426966	3987635	599.0
W11	Grd Mala-3	90.30	118.40	420.0	Alluvium+Bakhtiary	0.0-305.0	305.0-420.0	Unconfined	415045	3982303	423.0
W12	Qushtapa-12	142.15	249.90	500.0	Alluvium+Bakhtiary	0.0-285.0	285.0-500.0	Unconfined	413469	3982303	413.0
W13	Qultapa Yaba	118.30	183.30	400.0	Alluvium+Bakhtiary	0.0-300.0	300.0-400.0	Unconfined	412812	3979755	402.0
W14	Nawroz-13	94.40	139.60	350.0	Alluvium+Bakhtiary	0.0-350.0	-	Unconfined	407630	4003043	396.0
W15	Shadi-23	139.60	234.30	370.0	Alluvium	0.0-370.0	-	Unconfined	407808	4001980	398.0
W16	Bakhe Shar Park	79.40	121.80	216.0	Alluvium	0.0-216.0	-	Unconfined	411158	4005256	415.0
W17	C.Science-1	98.75	149.30	324.0	Alluvium	0.0-324.0	-	Unconfined	411772	4001204	422.0
W18	Bahar-4	96.00	126.50	250.0	Alluvium	0.0-250.0	-	Unconfined	408874	4002102	406.0
W19	Shorsh-8	81.30	121.20	300.0	Alluvium	0.0-300.0	-	Unconfined	412704	4008359	443.0
W20	Daratw-53	134.55	165.70	300.0	Alluvium	0.0-300.0	-	Unconfined	412561	3998602	433.0
W21	Grda rasha-4	102.40	172.10	360.0	Alluvium	0.0-360.0	-	Unconfined	411968	3995054	422.0
W22	Shawais-10	85.00	164.00	360.0	Upper Bakhtiary	0.0-140.0	140.0-360.0	Unconfined	417583	4012229	518.0
W23	Kasnazan-7	149.50	302.20	420.0	Alluvium+Bakhtiary	0.0-115.0	115.0-420.0	Unconfined	422639	4007342	627.0
W24	Sebirany Gawra	54.50	119.70	300.00	Alluvium+Bakhtiary	0.0-50.0	50.0-300.0	Unconfined	402134	4012027	380.0

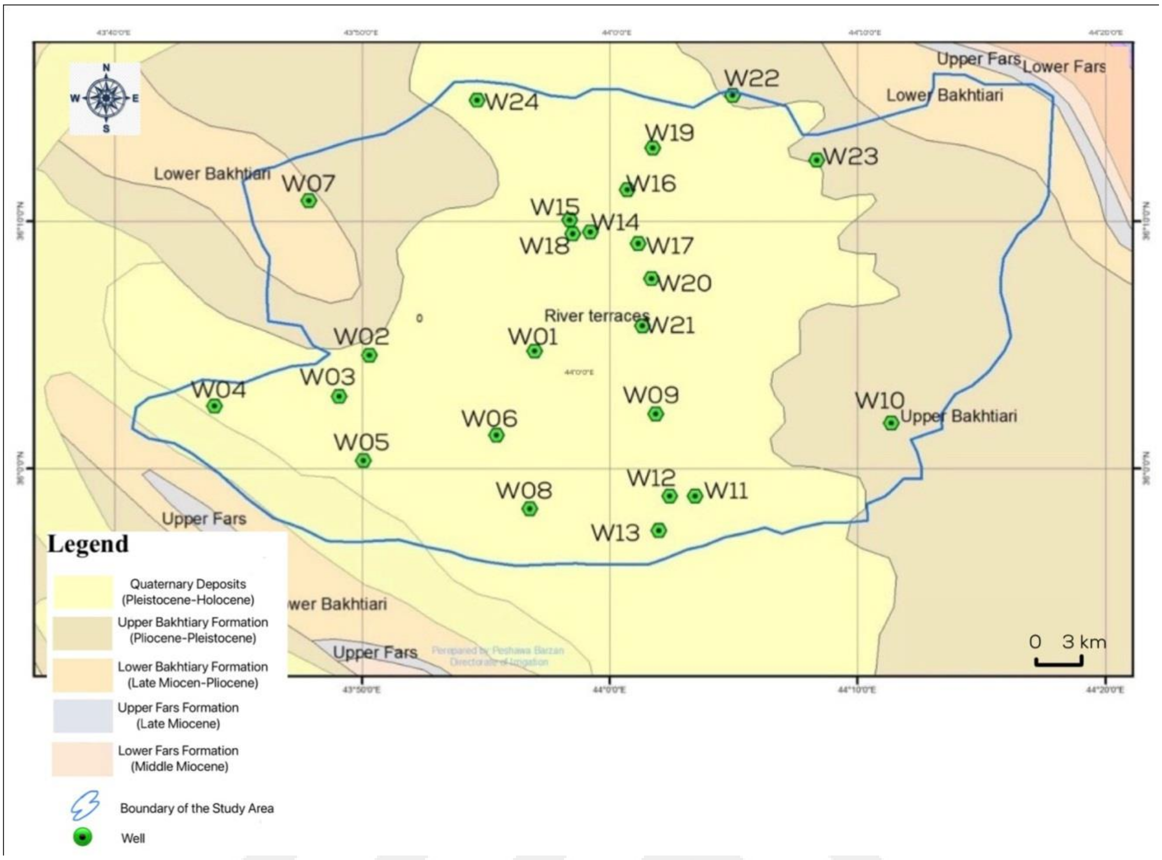

Figure 5.2. Location of the 24 wells on the Erbil Central sub-basin map.

Many factors influence the reliability of any geological formation being a water-bearing formation, including the physical properties of the sediments or rocks, the geometry of the geological formations, the spatial position of the formation in relation to other formations, elevation, and water quality. Because of the presence of reliable intergranular sediments, the Erbil Central sub-basin is a good aquifer (which is internally divided into several aquifer systems), and the porosity and permeability of the sediments are high enough to transport, store, and produce water. The aquifer dimensions (large saturation thickness) are sufficient to provide groundwater to wells. Because the Erbil Central sub-basin is shaped like a trough, the spatial arrangement of the rocks and deposits aids groundwater storage resulting in a typical aquifer.

Aquifers can be classified based on their location in the groundwater system. The classification is also influenced by groundwater levels measured in an observation well with a screen in the aquifer. Groundwater in unconfined aquifers is directly contact with the atmosphere. A perched aquifer is an unconfined aquifer that is not connected to any lower-level aquifers. Semi-confined aquitards are a type of aquitard that contains groundwater that isn't exposed to the air. Completely confined aquifers are found beneath the aquiclude. The Erbil Central sub-basin aquifer and aquitard extension vary vertically and laterally from place to place, with the aquifer system changing with depth. The Erbil Central sub-basin is considered a composite system basin by most experts. The following are the main characteristics of the main aquifers in Erbil Central sub basin:

5.2.1. Alluvium Aquifer

Quaternary deposits cover the majority of the study area, and they are the most important aquifer due to its extensive depth (maximum 350 meters) and high yielding water to wells. These sediments date from the Pleistocene to the Holocene age with gravel, clay, mix sand, silt, and silty clay alternate in their composition. Because the deposits are semi-cohesive and low compacted, in addition to the grain size ranging from fine to coarse, the physical and hydraulic properties (porosity, hydraulic conductivity, transmissivity, and specific storage) of the aquifer are in good condition. A large number of wells in the Erbil Central sub-basin are discharging from this aquifer. However, the hydraulic characteristics of the basins and the yield are not the same everywhere (it varies from low to high productivity due to many geological settings and stratigraphy), the majority of the wells are of good yield, with the exception of the wells located at the eastern part of the sub-basin. Due to the described alternation of sediments in the study area, it was possible to see the confined aquifer in Quaternary deposits 10 years ago.

5.2.2. Aquifers in Bakhtiary Formation

Upper Bakhtiary Formation (Bai Hassan Formation) is composed of conglomerates inter-bedded with sandstone and claystone. It is suggested that the thickness is less than 2000 m in Erbil Central sub- basin. Its productivity is better than the underlying Lower Bakhtiary Formation (Mukdadyia Formation) but it is also not a good productive formation in Central sub- basin. It may be due to the compaction of the sediments, and structural geology in the study area. The hydraulic properties of Quaternary deposits are significantly higher than that of the Upper Bakhtiary Formation aquifers. Many artesian wells were flowing in the study area, in the northeast and east parts, most are located and penetrated the Lower Bakhtiary - Upper Bakhtiary aquifers due to the upper and lower confining (aquitards) beds of claystone and siltstones (Figure 5.3).

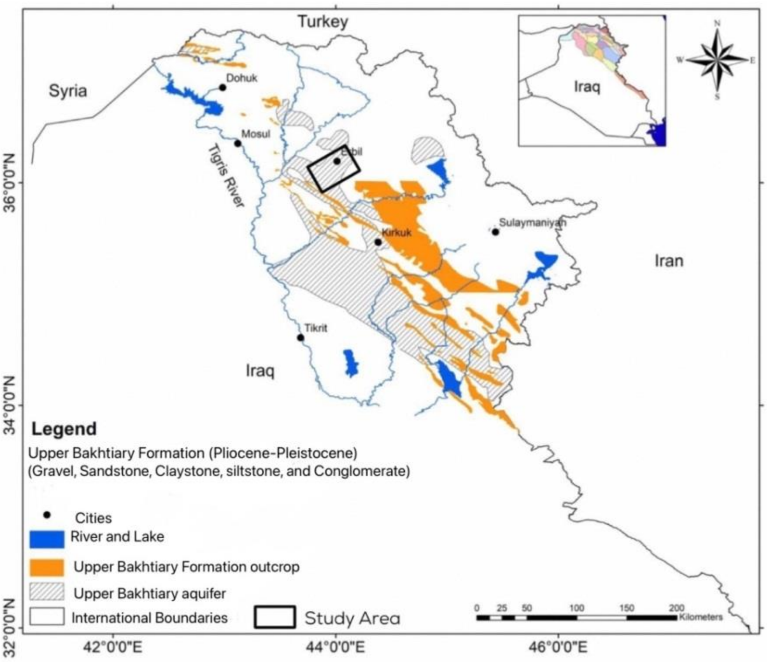

Figure 5.3. Outcrops of Upper Bakhtiary Formation at the northeast of Iraq and its aquifer (after Al Jawad and Ridha, 2008).

The Lower Bakhtiary Formation is composed of alternation of sandstones, siltstones, and lenses of mudstone. The thickness of the formation is suggested to be around 2000 m. In the study area only small numbers of the wells are drilled in Lower Bakhtiary Formation and they are with low yield, may be due to the same reasons as with the Upper Bakhtiary Formation (in the study area) (Figure 5.4).

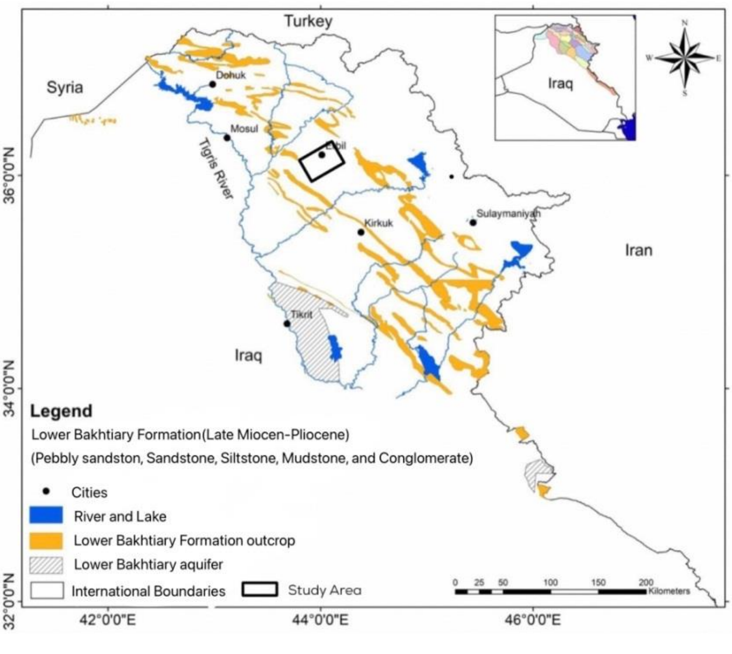

Figure 5.4. Outcrops of Lower Bakhtiary Formation at the northeast of Iraq and its aquifer (after Al Jawad and Ridha, 2008).

5.2.3. Elevation Map

The highest points are found in the basin's northeastern region. Many wells have been drilled in the northeastern section of the Erbil Central sub-basin area, which has high to medium elevations ranging from 480 to 680 metres. Water runoff flows from the highlands, settles, and accumulates in the lowland areas to the south and southwest on this part of the basin surface. Lower to moderately high areas, ranging in elevation from 280 to 440 m, are found in the southern and central parts of the basin, where the basin flattens and the terrain is dominated by areas of medium to low relief. The majority of the wells are in these low-lying areas. The region to the southwest represents the central sub- basin's lowest point (Figure 5.5). The slope of areas across the study area is one of the purposes of an elevation map. From the northeast, slopes encircle the Erbil basin. Aside from these slopes, slope angles in the basin generally decrease from northeast to southwest. The distribution and composition of bedrock are frequently reflected in topography. As a result, if these slopes follow the structural patterns prevalent across the basin, they may be able to forecast bedding level drops and show aquifer retreat trends. The map also depicts runoff flow paths. Water flows naturally towards flat areas, avoiding heights where it cannot settle. Water will most likely pool in flat regions, where it will ultimately seep out and recharge groundwater.

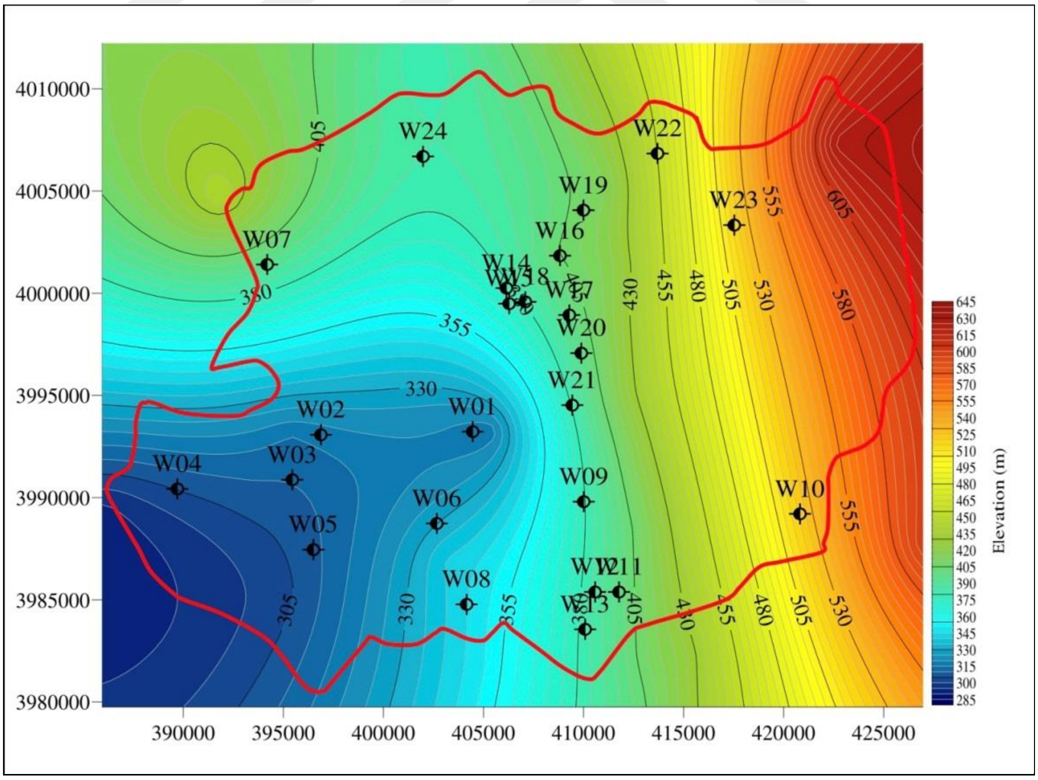

Figure 5.5. Ground surface's elevation map of Erbil Central sub-basin.

5.2.4. Groundwater Flow

The location of higher groundwater elevation determines the flow direction of groundwater. The direction in which the water flows is determined by the distribution of hydraulic heads in the saturated zone (Uliana, 2004). The flow of groundwater is controlled by the laws of physics and thermodynamics. Gravity, external pressure (atmospheric pressure), and molecular attraction are the three main factors that influence groundwater movement. A contour map of groundwater elevations has been drawn to visualize groundwater movement, with flow direction dependent on groundwater elevations (head). Each contour line (equipotential line) in the basin corresponds to the same groundwater level (hydraulic head) (Figure 5. 6). In typical isotopic aquifers, the flow lines intersect the equipotential lines at right angles, and inhomogenous aquifers which lithology, pumping, and subsurface structures don't disturb the flow movement the equipotential lines become straight lines, and the flow lines are also straight perpendicular to equipotential lines. From the flow net (equipotential lines and flow directions) of the study area and around, the following notes were observed:

1- Groundwater depression in Erbil's city center, with equipotential lines bending in the flow direction and flow directions pointing to Erbil's center (low potential hydraulic head). This is due to the area's overexploitation through pumping.

2- The topography of the area is reflected in the topography of the groundwater, and the hydraulic head is higher on higher ground (eg. in the eastern part of the study area).

3- Changing the flow direction around the Qoritan Chukul (W01) fault by bending equipotential lines. Significant differences in groundwater levels can occur across faults if the fault zone is composed of finely ground rock and clay, according to Qurtas (2013).

4- Direction of groundwater is divided into two opposite directions along the boundary to differentiate the central and Bashtapa sub-basins of the Erbil Plain. The same boundary divides the Greater Zab and Lesser Zab rivers.

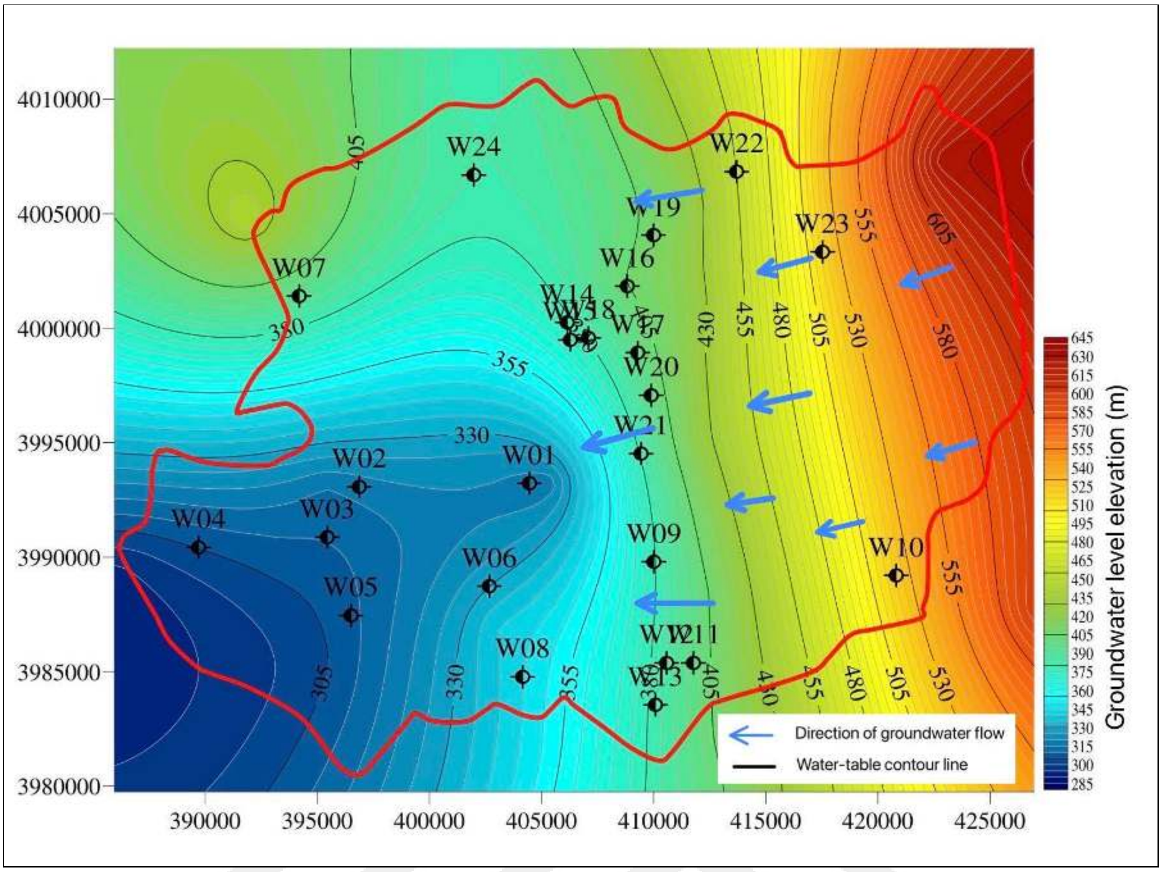

Figure 5. 6. Water-table contour lines and groundwater flow direction in the study area.

It is noted that the surface flow is somehow identical to the groundwater flow (Qurtas, 2013). The steep hydraulic head gradient companied with the low transmissivity, this approves that the hydraulic gradient (dh/dl) is high the transmissivity is low and vice versa. This phenomenon is due to lithological and structural variations in the east part of the study area.

5.2.5. Depth Map

To analyze the underlying geology of the Erbil Central sub-basin, the total depth of each drilled well to the specified aquifer is employed. Several areas of up and down warping are depicted on the maps across the basin. Various underlying geologic features, as well as several shall owing and deepening tendencies, are depicted on the depth maps. This shape is particularly visible on the Erbil Central Sub-Basin composite map. In the western central sub-basins and the southwestern regions of the map, shallow depths are plainly visible. The east and central parts of the basin are, on average, the deepest. (Figure 5.7). The depth of the wells increases in the south of the sub-basin related to the low hydraulic conductivity of the lithological units. Furthermore, many legal and illegal wells were drilled in this part of the sub-basin due to the increasing demand on groundwater of factories, farms, and fisheries in this part of the sub-basin. However, the depth of the wells decreases in the southwest and north of the sub-basin related to the higher hydraulic conductivity of geological units. All depth map interpretations are compatible with the overall surface geology, showing that the basin was not immune to local tectonics and that these changes are most likely due to tectonic activity, which generated faulting and folding to the basin's north and northeast.

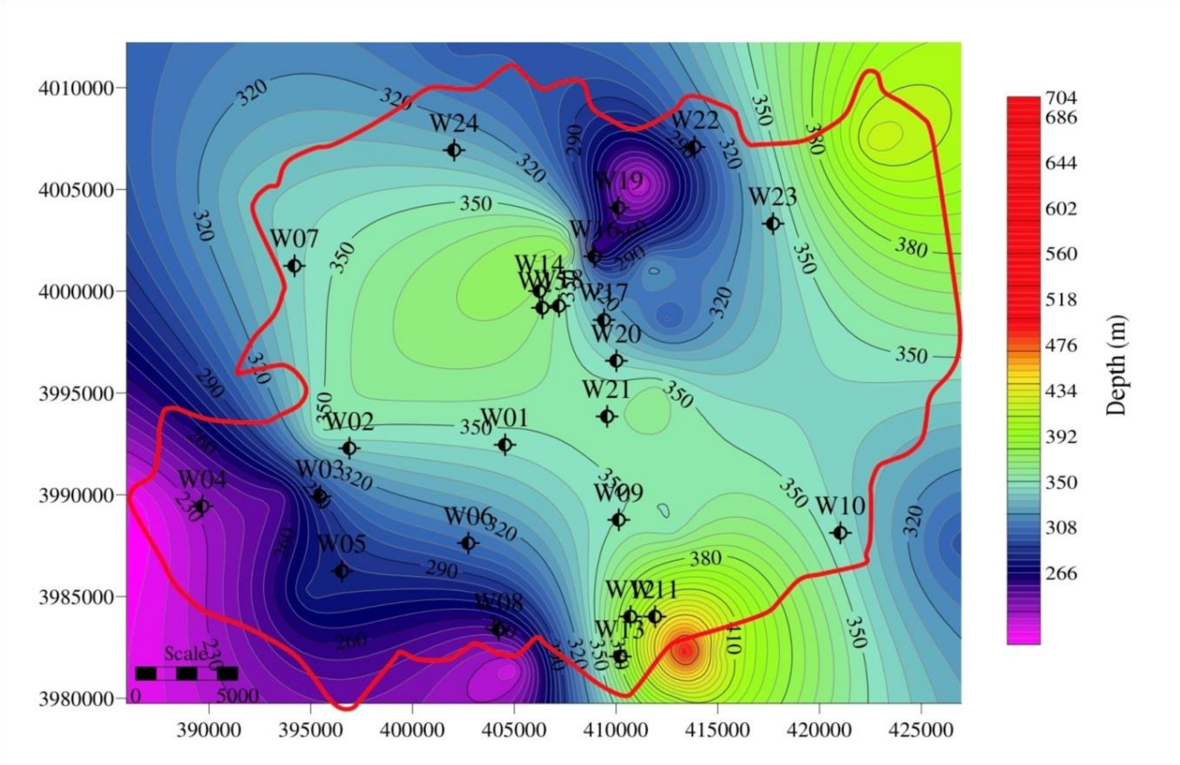

Figure 5.7. Contour map showing the depth of 24 monitoring wells in the Erbil Central sub-basin.

5.2.6. Lithological Columns of Wells

The objective of building cross-sections of an aquifer is to estimate the geometry of the entire sub-basin and to calculate the approximate distribution and thickness of the underground Quaternary deposits' aquifer and Bakhtiary formation's aquifers. Although the ability to hold and transport groundwater is controlled by the rock layers and their physical properties such as porosity and hydraulic conductivity, the lithological columns of wells show how the geometric distribution of these water-bearing aquifers has a significant impact on groundwater flow in the study area.

The A-A' profile through the alluvium is oriented from N to S and includes seven wells (W19, W18, W20, W21, W09, W12, and W13). The thickness of the alluvium can reaches more than 300 m in the north, and 350 meters in the middle of the sub-basin, In the southern part of the sub-basin the lithological units of Upper Bakhtiary Formation determined at 286 m and 300 m depths related to the lithological columns for W12 and W13 wells (Figure 5.8). No significant change has been observed in the static water levels in alluvial aquifers, and the static water level is generally between 70 and 80 m.

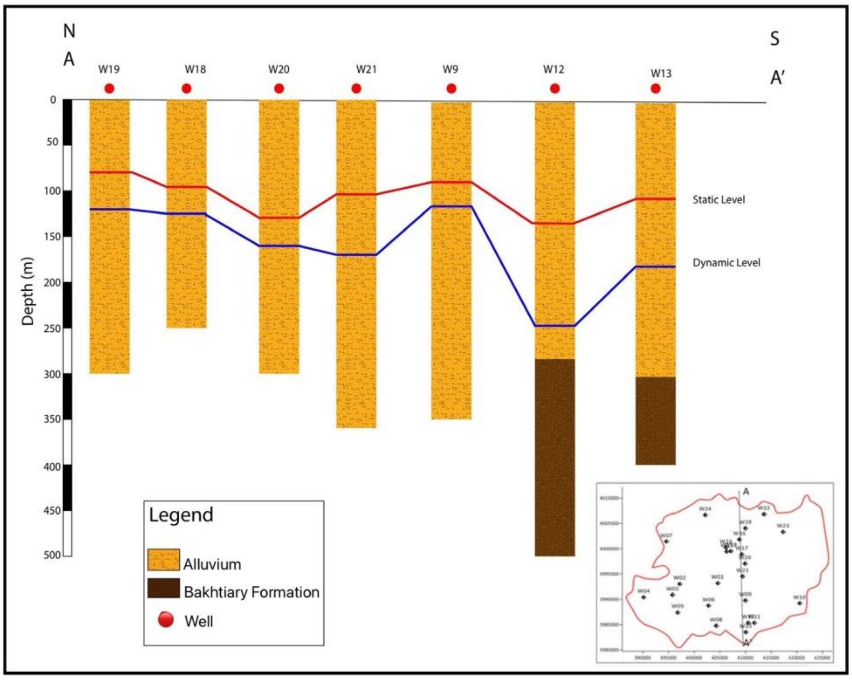

Figure 5.8. The lithological columns of wells across section along A-A' profile in alluvium aquifer.

The B-B profile is oriented from NE to SW and includes seven wells (W04, W03, W02, W14, W15, W16, and W23) (Figure 5.9). This profile shows the distribution of alluvium and Bakhtiary formations's aquifers. The thickness of the alluvium aquifer reaches 50 m to 85 m in the southwestern part, and the Bakhtiary Formation appears after this depth. The depth of the wells does not reach to the Bakhtiary Formation in the central part, but the Bakhtiary Formation appears after a depth of 100 m in the northeastern part of the Erbil central sub-basin (Figure 5.9). The drawdown between static and dynamic water levels is greater in W15 and W23 wells. The reasons for the greater drawdown in W15 are related to the high population and excessive water pumping, whereas the drawdown in W23 is due to the location of the well. W23 well is drilled at higher elevations on the recharge zone of the sub-basin (Table 5.1).

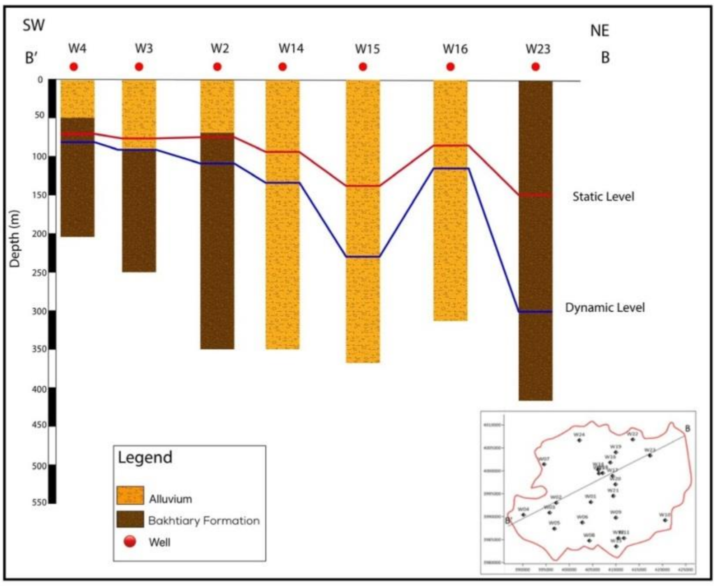

Figure 5.9. The lithological columns of wells along B-B' profile in study area.

The C-C' profile is oriented from NW to SE and includes five wells (W07, W01, W21, W19, and W10). This profile shows the distribution of the alluvialalluvium and Bakhtiary Formation's aquifers in the groundcentral sub-basin. The Lower Bakhtiary Formation appears in the northwestern part of the surface to a depth of more than 330 m, and in the central part, the thickness of the alluvium is more than 350 m. The Upper Bakhtiary Formation appears in the southeastern part of the central sub-basin to a depth more than 300 m (Figure 5.10). The W10 well drilled at higher altitude, on the recharge zone of the central sub-basin, and recharging from a perched aquifer in Upper Bakhtiary' lithological units. Because of this reasons, the drawdown in this well is grater compare to the other wells (Table 5.1).

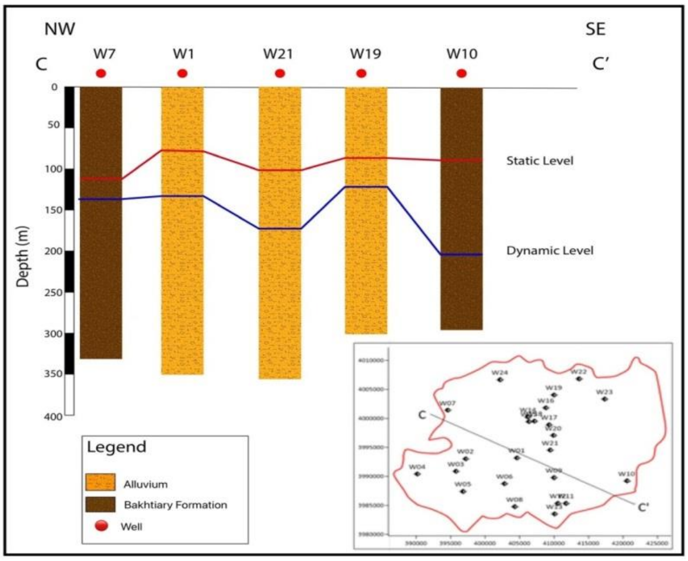

Figure 5.10. The lithological columns of wells along C-C' profile in study area.

The depth of the groundwater level in the north of the Erbil Central sub-basin can be estimated between 80 and 95 m. Furthermore, in the central parts of the sub-basin the depth of the groundwater level is estimated between 70 and 140 m, while in the south of the sub-basin the groundwater level is between 120 to and 140 m (Figure 5.8). The depth of groundwater level ranges between 90 to 150 m in the Bakhtiary Formation aquifer in the eastern part of the central sub-basin, whereas it ranges between 70 to 115 m in the same aquifer in the western part of the central sub-basin (Figure 5.9; Figure 5.10). Due to the shallowness and depth deepness of these aquifers from the surface of the earth at each well location, it implies a significant difference in groundwater level across the whole basin.

5.3. Hydraulic Properties of Aquifers

Pumping tests were used to obtain the hydraulic parameters of aquifers, with the help of drilling well profiles, which were carried out in the area for estimating saturated thickness for the aquifers, within the selected sites. Estimating the physical properties of water-bearing layers is a critical component of groundwater research.

Conducting and analyzing aquifer tests, which is a costly method, is one of the most effective ways of determining these properties. Alternatively, when observation wells are not available, the physical properties of the aquifer can be estimated using a single-well test (Kruseman et.al, 1994; Dellur, 1999; Schaaf, 2004). Many researchers use this method, including Hasan (1981); Hassan (1998); Chnaray (2003); Aqrawi (2003); Ali (2007); Al Manami (2008); Hama amin (2011); Masoud (2013). Well tests were performed on 24 wells that penetrated various aquifers for the current study.

5.3.1. Pumping Tests of Wells

The transmissivity (T), hydraulic conductivity (K), specific yield (Sy), and storage coefficient (S) parameters can be calculated using the computer program AQTESOLV, which can be used on single-well tests as well as partially and fully penetrating cases.

In a single-well test, drawdown measurements are obtained in the test (control) well. Analyzing a single-well test is no different than a test with observation wells. AQTESOLV provides the same rich set of tools for analyzing single-well tests as multi-well tests.

One crucial aspect of single-well tests is the wellbore storage effect on early-time data. AQTESOLV includes wellbore storage (finite-diameter well) solutions for confined, leaky confined, unconfined, and fractured aquifers. AQTESOLV provides an unmatched number of solution methods for the analysis of single-well tests with wellbore storage.

Pumping tests can provide information on the characteristics of the water-bearing formations and the well. The pumping test data is used to evaluate the hydraulic parameters of the aquifer, such as hydraulic conductivity, transmissibility, storage coefficient, specific yield leakage factor, and hydraulic resistance. A pumping test will also reveal information about the well site's hydrogeological properties, such as the type of aquifer, its extent, and thickness, water table gradient, and recharge boundaries (Michael and Khepar, 1989). The data from well tests performed in 24 selected wells were analyzed in the study area.

Duration of Pumping Test

The kind of aquifer, its hydraulic parameters, and the method for assessing pumping test data all influence the length of the pumping test. If pumping continues until a nearly steady-state condition is reached, reliable data can be obtained. In a semi-confined aquifer, this condition can be achieved in 15 to 20 hours. In a confined aquifer, the duration should be between 24 to 40 hours. However, waiting until the steady-state condition is reached is not always necessary (Michael and Khepar, 1989).

Recovery Test

The water level in the well and the observation wells begins to rise when the pump is stopped at the end of a pumping test. The process is known as groundwater level recovery. The decline in water level (drawdown) below the original static water level (before pumping) and throughout the recovery time is referred to as residual drawdown. By analyzing the residual drawdown, the aquifer's transmissibility can be calculated, providing an independent check on the pumping test results. During the recovery period, the rate of recharge to the well is assumed to be constant, whereas controlling the pumping rate in the field becomes difficult. Furthermore, in the absence of an observation well, measurements of recovery can be made in the well during a recovery test. Jacob's method was used to determining hydraulic conductivity and transmissibility of the aquifers in the studied area. The Jacob method plots the drawdown versus time on semi-logarithmic paper

Jacob Straight Line Method

Jacob's method was used to analyze data from well-pumping tests (Jacob, 1948) observed that values of transmissivity can be obtained by noting that t/to =10 (one logarithmic cycle), then log t/to = 1, and if s is the drawdown difference per log cycle of t, then the equation below can be used to determine transmissivity (Todd, 2005).

$$T = 0.183\ Q/\Delta s \qquad (5.6)$$

Correction drawdown calculated according to Serrano, 1997:

$$S^{*}=s- S2/2b \qquad (5.7)$$

$$T = T / b \qquad (5.8)$$

Where:

T: Transmissivity (m^2/day)

Q; Pumps constant rate discharge from the well (m^3/day)

Δs: Difference of drawdown per log cycle t.

K: Hydraulic conductivity (m/day)

B: Saturated thickness (m)

S*: Correction drawdown (m)

S: Drawdown value (m)

t/to: Time of last record / initial time

The Jacob technique was used to compute transmissivity and hydraulic conductivity on semi-logarithmic paper based on the connection between corrective drawdown and time drawing (Todd, 2005) (Table 5.2; Figure 5.11; Appendix 5)

Table 5.2. Hydraulic conductivity (K) (m/day) of the aquifers calculated by Jacob Method.

Well No.	Well name	Q-discharge (m^3/day)	T-Transmissivity (m^2 /day)	b-Saturated thickness (m)	K - Hydraulic conductivity (m/day)
W 01	Qoritan chukul-4	635.04	1.83	238.00	0.0077
W02	Tandura	1568.16	6.10	268.00	0.0228
W03	Mastawa	1587.60	183.30	162.00	1.1315
W04	Shekhsherwan	1944.00	45.62	125.00	0.3650
W05	Grd azaban	1555.20	14.51	88.00	0.1649
W06	Perdawd	1587.60	20.77	252.00	0.0824
W07	Satoor	822.96	3.33	180.00	0.0185
W08	Dugrdkan	596.16	14.77	165.00	0.0895
W09	Murtka Shahab	1347.84	29.38	130.00	0.2260
W10	Bestanay gawra	194.40	0.53	140.00	0.0038
W11	Grd Mala-3	1075.68	13.14	230.00	0.0571
W12	Qushtapa-12	732.24	2.53	181.00	0.0140
W13	Qultapa Yaba	648.00	1.57	224.00	0.0070
W14	Nawroz-13	1166.40	13.79	227.00	0.0607
W15	Shadi-23	972.00	2.288	279.00	0.0082
W16	Bakhe shar park	712.80	14.04	111.00	0.1265
W17	C.science-1	486.00	3.84	158.00	0.0243
W18	Bahar-4	1425.60	27.38	149.00	0.1838
W19	Shorsh-8	168.48	0.68	140.00	0.0049
W20	Daratw-53	1166.40	9.79	190.00	0.0515
W21	Grda rasha-4	550.80	1.62	225.00	0.0072
W22	Shawais-10	648.00	1.76	236.00	0.0074
W23	Kasnazan-7	356.40	0.76	281.00	0.0027
W24	Sebirani gawra	1166.40	3.61	211.00	0.0171

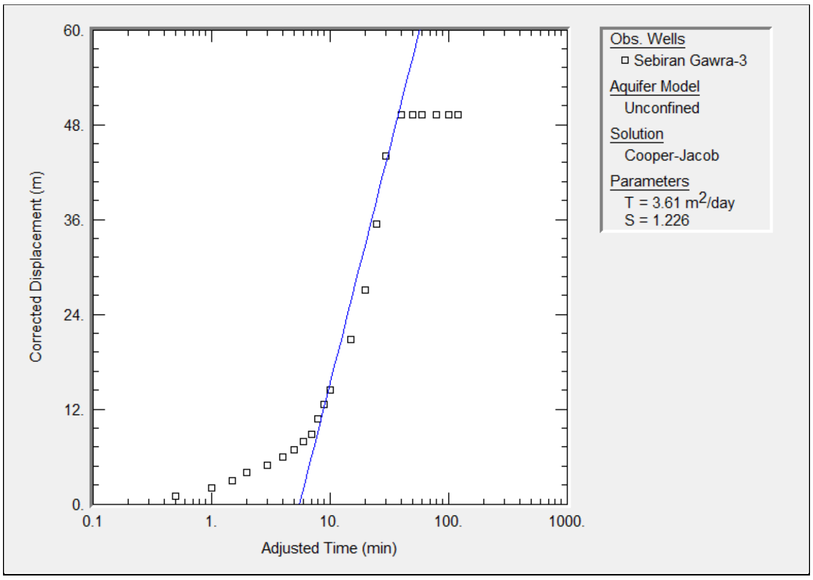

Figure 5.11. Analysis of drawdown and recovery data with a derivative from a constant-rate single-well pumping test in an unconfined aquifer. Early-time data show wellbore storage effect before derivative becomes constant (Sebirany Gawra well)

5.3.2. Hydraulic Conductivity

The capacity of a soil or rock to transport fluids is defined by a variety of physical parameters such as porosity, particles, and other elements (Deming, 2002).

Coarse-grained sands and gravels have high hydraulic conductivities and transfer water well. Water transmission is weak in fine-grained silts and clays, and hydraulic conductivities are low (in the 0.001-0.1 m/day range). Hydraulic conductivity is represented as:

$$K = V/(dh/dl) \tag{5.1}$$

where:

K: Hydraulic conductivity (m/day)

V: Groundwater velocity (m/day)

dh/dl: Hydraulic gradient

The hydraulic conductivity value determined by using an AQTESOLV on selected wells in the study area is shown in Table 5.2 and Figure 5.12.

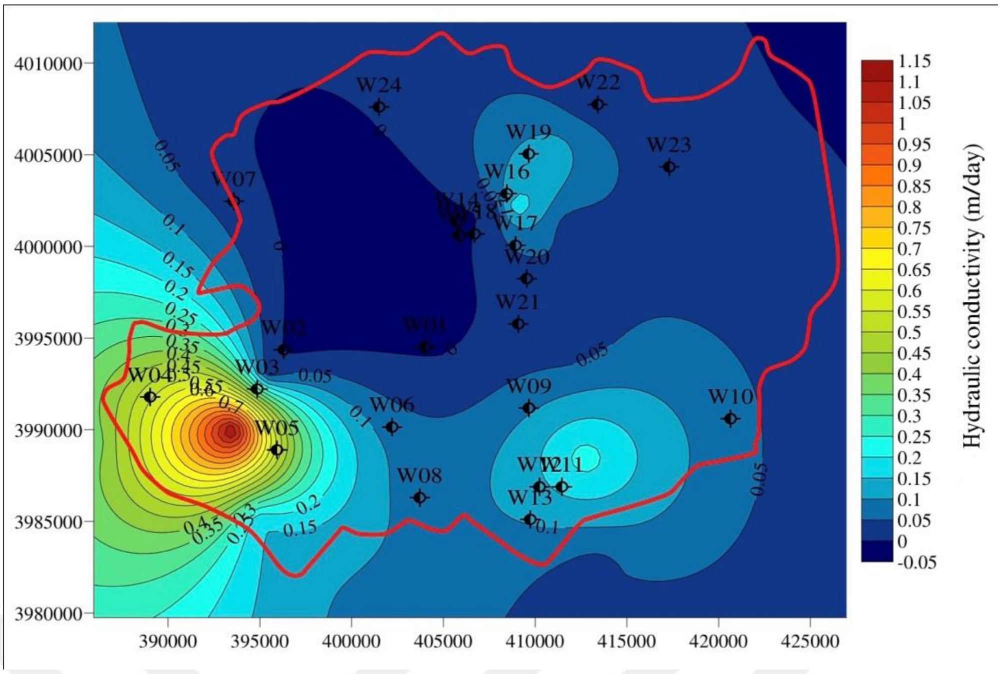

Figure 5.12. Contour map showing variation of hydraulic conductivity in the study area.

The wells located in the eastern and northeastern regions are drilled on the Bakhtiary formation, such as the W10 and W22 wells that have low hydraulic conduactivity. The low hydraulic conductivity in these parts of central sub-basin must be related to the thick layers of claystone and siltstone in Bakhtiary Formation. Furthermore, silty and clayey layers are dominant in Quaternary deposits in the sub-basin's central part resulting in lower hydraulic conductivity. In contrast, the thickness of gravely and sandy layers must be greater than the silt and clay layers in Quaternary deposits that reflect high hydraulic conductivity in the southwestern part of the central sub-basin.

5.3.3. Transmissivity

It is the rate at which prevailing density and viscosity water is transmitted through a unit width of an aquifer or confining bed under a unit hydraulic gradient. It is determined by the liquid's properties, and the porous media's thickness (Fetter, 1994). Transmissivity is the product of hydraulic conductivity and aquifer saturated thickness:

$$T=b*K \tag{5.2}$$

where;

T: Transmissivity (L^2/t) (m^2/d)

B: Saturated thickness (L) (e.g. m)

K: Hydraulic conductivity (e.g. m/d). In the study area, the value of transmissivity has been estimated through pumping test data.

The transmitivity value determined by calculated using the computer program AQTESOLV on selected wells in the study area is represented by Table 5.2 and Figure 5.13.

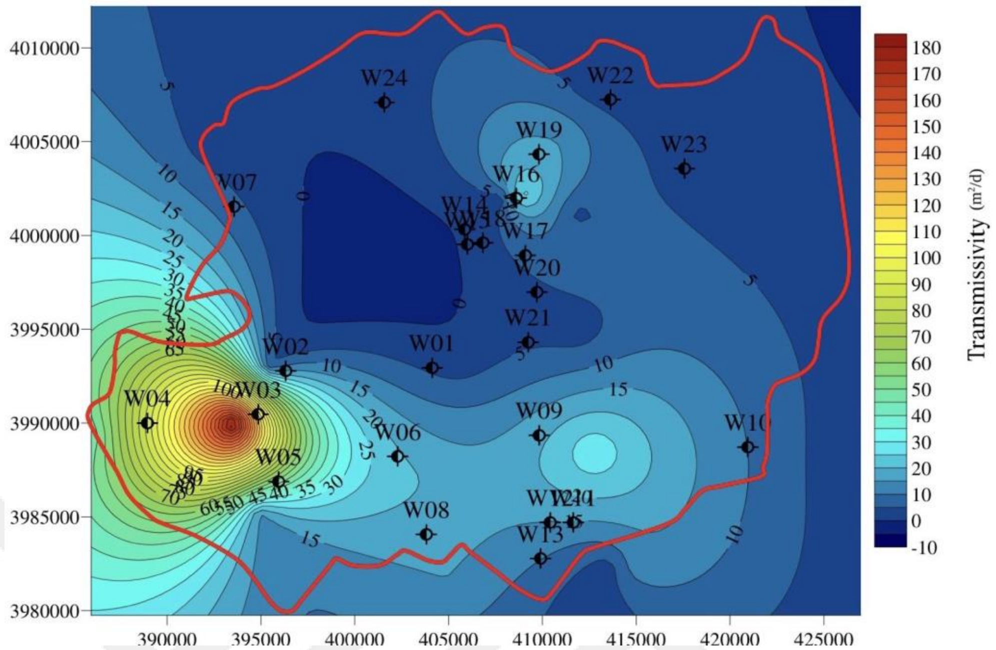

Figure 5.13. Contour map showing variation of transmissivity in the study area.

Wells located on the eastern and central sides of the study area has the lowest value of transmissivity than the southwest side, due to the increase in the hydraulic conductivity value and the thickness of the saturated aquifer. Because of the inverse relationship between transmissivity and drawdown, W03 well has the highest transmissivity value and the lowest value of drawdown whereas, the W10 well has the lowest value of transmissivity and the highest drawdown (Table 5.2).

Some wells have a low flow rate (less than 194.4 m^3/day) and they have high drawdowns (more than 111m), such as Bestanay Gawra well (W10). They are penetrating mostly complex aquifers. These wells are deemed low-yielding and must be improved.

Some wells have high transmissivity 183.3 m^2/day and high discharge (more than 1587.6 m^3/day) and their drawdown are less than 4 m. They are mostly penetrating the Bakhtiary Formation aquifer, such as Mastawa well (W03) (Table 5.2). It is feasible to modify the pumping rate and raise the discharge rate of the wells.

Some wells have low transmissivity of 0.75 m^2/day, and their discharge rate is not high (356 m^3/day). Because the drawdown in these wells exceeds 86 m, the low rate of discharge will have a negative impact on the productivity of the wells, perhaps leading to failure or even dryness in the future.

5.3.4. Storage coefficient

The coefficient of storage is used to characterise the storage qualities of confined and semi-confined aquifers. It is defined as the volume of water that the aquifer releases from or receives into storage per unit surface area of the aquifer per unit change in the component of head normal to the surface. Water recharge or discharge from an aquifer represents a change in the aquifer's storage volume.

$$S = (V / A)/h \tag{5.3}$$

where

S: Represents storativity.

V: The amount of water obtained or lost.

A: The surface area of the aquifer impacted by the recharge or discharge

H: Represents the average water level decline.

This is simply defined as the product of the volume of aquifer lying between the water table at the beginning and end of the time period and the formation's typical specific yield for unconfined aquifers (Todd, 2005). The storage coefficient (S) value determined by using AQTESOLV software on selected wells in the study area is shown in Table 5.3 and Figure 5.14.

Table 5.3. Storage coefficient of the aquifers in the studied area.

Well No.	Well name	T-Transmissivity (m^2 /day)	S-Storage coefficient (dimensionless)
W 01	Qoritan chukul-4	1.83	0.66
W02	Tandura	6.10	1.14
W03	Mastawa	183.30	0.33
W04	Shekhsherwan	45.62	15.40
W05	Grd azaban	14.51	5.17
W06	Perdawd	20.77	1.16
W07	Satoor	3.33	0.30
W08	Dugrdkan	14.77	0.63
W09	Murtka Shahab	29.38	0.02
W10	Bestanay gawra	0.53	0.02
W11	Grd Mala-3	13.14	0.07
W12	Qushtapa-12	2.53	0.18
W13	Qultapa Yaba	1.57	0.96
W14	Nawroz-13	13.79	3.14
W15	Shadi-23	2.29	0.83
W16	Bakhe shar park	14.04	0.63
W17	C.science-1	3.84	0.05
W18	Bahar-4	27.38	6.40
W19	Shorsh-8	0.68	0.21
W20	Daratw-53	9.79	4.93
W21	Grda rasha-4	1.62	0.47
W22	Shawais-10	1.76	0.55
W23	Kasnazan-7	0.76	0.24
W24	Sebiran gawra	3.61	1.23

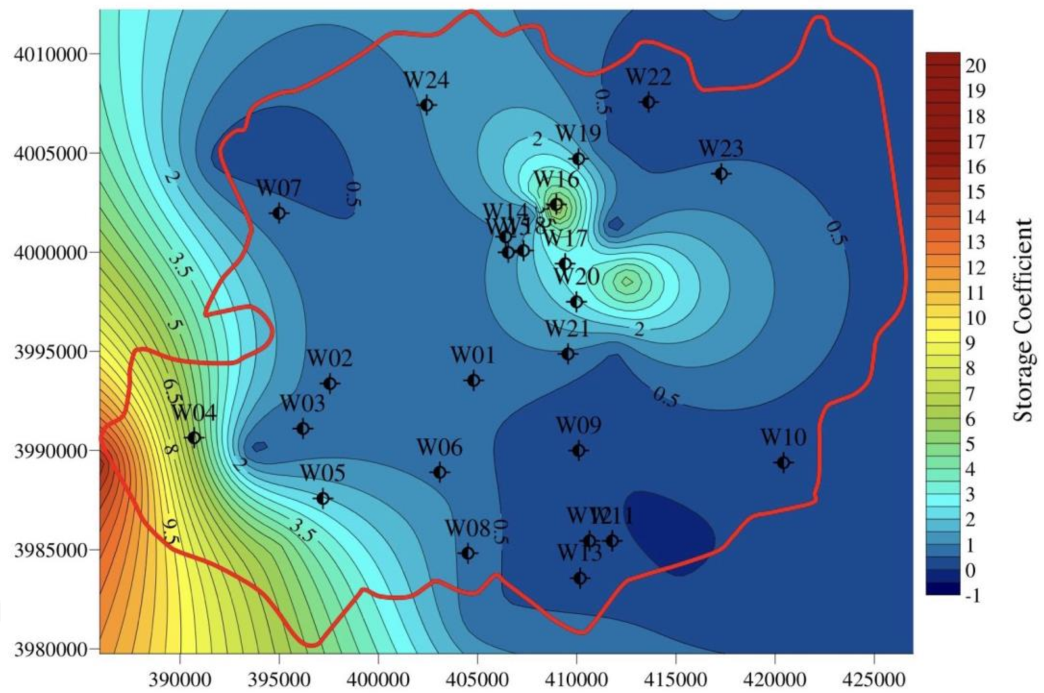

Figure 5.14. Contour map showing variation of storage coefficient in the study area.

The volume of groundwater stored in an aquifer depends on the porosity, but not all of the water stored in the pore spaces can be extracted, or will drain under the force of gravity. For this reason when we define aquifer storage what is really meant is yield.

The southwestern regions have the highest values of hydraulic conductivity and storage coefficient, and the wells in the region consist of sand and gravel, so the productivity of the well is 220 g/m, while the eastern regions have the lowest values of hydraulic conductivity and storage coefficient, which consist of mud and silt and the productivity of the well is 30 g/m.

5.3.5. Specific Yield

An aquifer's specific yield is the quantity of water that a unit volume of the aquifer will give when drained by gravity. When exposed to gravity drainage, the fractions or percentages of water maintained in the aquifer mass are compared to the water retained in a unit volume of the aquifer. The porosity of the aquifer is equal to the sum of the specific yield and specific retention. The specific yield was calculated using the following formula:

$$Sy = \frac{wy}{\mathrm{v}} \tag{5.4}$$

where:

Sy: Specific yield

Wy: Water spent size (m^3)

V: Total volume (m^3)

The specific yield (Sy) value determined by using an aquifer test on selected wells in the study area is shown in Table 5.4 and Figure 5.15. The wells' specific yield can be calculated using Johnson (1955) formula (Table 5.4).

$$Sy = \frac{saturated\ thickness(b)}{1000} \tag{5.5}$$

The geological profile, which is represented by the producing stratum, determines the thickness of saturation (the permeable strata that contain water).

Table 5.4. Specific yield calculated according to Johnson (1955) formula

Well No.	Well Name	b- Saturated thickness of the aquifer (m)	Sy- Specific yield
W01	Qoritan chukul-4	238.00	0.24
W02	Tandura	268.00	0.27
W03	Mastawa	162.00	0.16
W04	Shekhsherwan	125.00	0.13
W05	Grd azaban	88.00	0.09
W06	Perdawd	252.00	0.25
W07	Satoor	180.00	0.18
W08	Dugrdkan	165.00	0.17
W09	Murtka Shahab	130.00	0.13
W10	Bestanay gawra	140.00	0.14
W11	Grd Mala-3	230.00	0.23
W12	Qushtapa-12	181.00	0.18
W13	Qultapa Yaba	224.00	0.22
W14	Nawroz-13	227.00	0.23
W15	Shadi-23	279.00	0.28
W16	Bakhe shar park	111.00	0.11
W17	C.science-1	158.00	0.16
W18	Bahar-4	149.00	0.15
W19	Shorsh-8	140.00	0.14
W20	Daratw-53	190.00	0.19
W21	Grda rasha-4	225.00	0.26
W22	Shawais-10	236.00	0.24
W23	Kasnazan-7	281.00	0.28
W24	Sebirani gawra	211.00	0.21

The specific yield of the aquifers in the central part of the study is higher, whereas it is low in the southweastern part of the Erbil Central sub-basin (Figure 5.15).

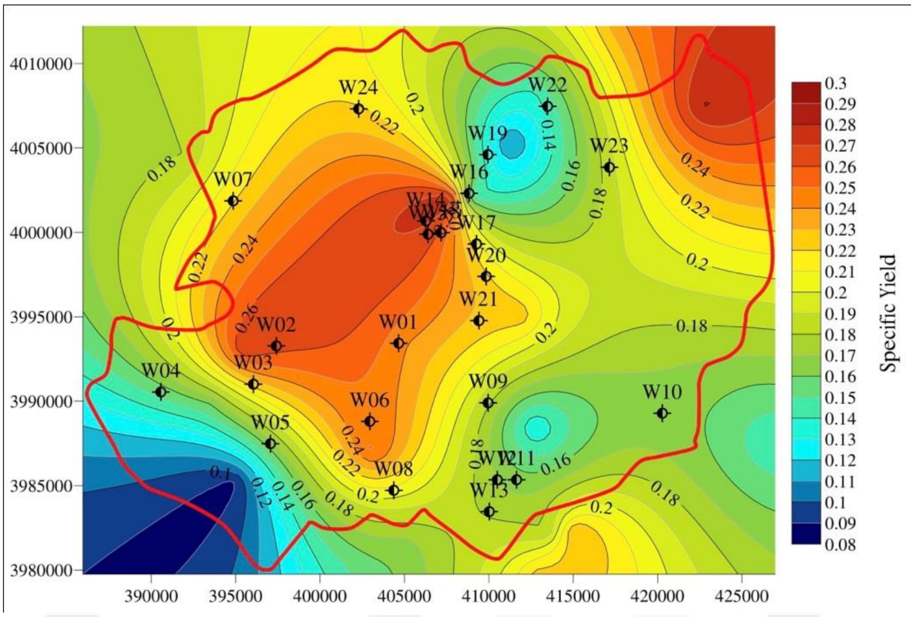

Figure 5.15. Contour map showing variation of specific yield in the study area.

The specific yield of clays is low at only 3% compared to values of around 20% for gravels or sands. In other words, gravels drain much more freely. The larger the specific yield, the more water an aquifer produces for each meter a water table is lowered by pumping. However, this concept of specific yield only applies to unconfined aquifers where changes in storage represent actual dewatering or drainage of the pore spaces.

Many factors seemed to have influenced well yields in the research region, including:

- Aquifer lithological features.
- The depth of the well varies.
- The type of pumping equipment used and the pump's capacity.

5.4. Specific Capacity

A well's specific capacity is the value of discharge available for a unit drawdown and is expressed in cubic meters per day for each meter of drawdown. It is a measure of a well's productivity; obviously, the higher the specific capacity, the better the well (Todd, 2005). Because an increase in drawdown decreases the effective thickness of the aquifer, the specific capacity values for wells in unconfined aquifers are not constant. Even after accounting for energy losses at the well, the specific capacity for the water table case would decrease with discharge.

The following two points summarize the utility of the specific capacity:

1. Providing an approximate estimate of transmissivity.
2. It is applicable to confined, unconfined, and fractured aquifers.

The specific capacity of the wells can be calculated using Al- Sawaf's (1977) formula:

$$Sc = \frac{HQ}{(TD - S.W.L)S} \tag{5.9}$$

where:

Sc: Specific Capacity

Q: The discharge of the well (m^3/day)

H: Saturated thickness (m)

TD: Total depth of the well (m)

S.W.L: Static water level (m)

S: Drawdown of the well (m)

According to Fetter (1994), the specific capacity is equivalent to the well's discharge divided by drawdown:

$$Sc = Q/S \tag{5.10}$$

Where

Q: The discharge of the well (m^3/day)

S: Drawdown of the well (m)

Because Al-Sawaf (1977) uses the saturated thickness, which is less than the total depth penetrated by the well, the determined specific capacity values are less than those determined by Fetter (2018). As a result, Fetter's results are better than Al- Sawaf's (Table 5.5; Figure 5.16).

Table 5.5. Specific capacity of the wells in the studied area

Well No.	Well name	Q (M^3/day)	S (m)	TD (m)	S.W.L (m)	H-Saturated thickness (m)	Sc m^3/day by Fetter (1994)	Sc m^3/day by Al-Sawaf (1977)
W01	Qoritan Chukul-4	635.04	61.00	350.00	68.00	238.00	8.79	10.41
W02	Tandura	1568.16	30.00	350.00	35.00	268.00	44.47	52.27
W03	Mastawa	1587.60	4.00	250.00	48.00	162.00	318.31	396.90
W04	Shekh Sherwan	1944.00	7.00	205.00	34.00	125.00	203.01	277.71
W05	Grd Azaban	1555.20	49.00	280.00	25.00	88.00	10.95	31.74
W06	Perdawd	1587.60	26.00	302.00	46.00	252.00	60.11	61.06
W07	Satoor	822.96	26.00	33500	59.00	180.00	20.64	31.65
W08	Dugrdkan	596.16	16.00	220.00	34.00	165.00	33.05	37.26
W09	Murtka Shahab	1347.84	31.00	350.00	74.00	130.00	20.48	43.48
W10	Bestanay Gawra	194.40	111.00	298.00	11.00	140.00	0.85	1.75
W11	Grd Mala-3	1075.68	31.00	420.00	90.00	230.00	24.18	34.70
W12	Qushtapa-12	732.24	84.00	420.00	75.00	181.00	4.57	8.72
W13	Qultapa Yaba	648.00	62.00	400.000	126.00	224.00	8.54	10.45
W14	Nawroz-13	1166.40	16.00	350.00	69.00	227.00	58.89	72.90
W15	Shadi-23	972.00	79.00	370.00	91.00	279.00	12.30	12.30
W16	Bakhe Shar Park	712.80	25.00	216.00	54.00	111.00	19.54	28.51
W17	C.Science-1	486.00	42.00	324.00	93.00	158.00	7.91	11.57
W18	Bahar-4	1425.60	25.00	216.00	47.00	149.00	50.28	57.02
W19	Shorsh-8	168.48	42.00	300.00	77.00	140.00	2.52	4.01
W20	Daratw-53	1166.40	18.00	300.00	70.00	190.00	53.53	64.80
W21	Grda Rasha-4	550.80	75.00	360.00	76.00	225.00	5.82	7.34
W22	Shawais-10	648.00	71.00	360.00	79.00	236.00	7.67	9.13
W23	Kasnazan-7	356.40	86.00	420.00	139.00	281.00	4.14	4.14
W24	Sebirany Gawra	1166.40	57.00	300.00	40.00	211.00	16.61	20.46

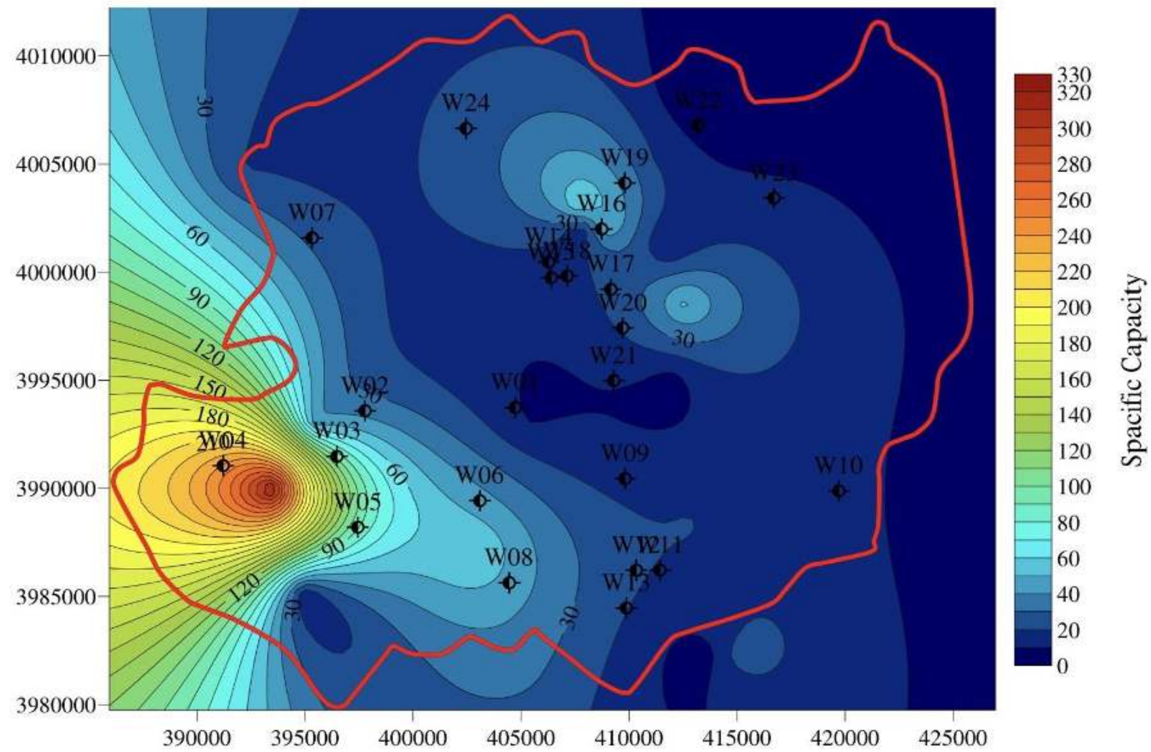

Figure 5.16. Contour map showing variation of specific capacity in the study area values calculated according to the Fetter (1994) formula were used.

Estimates of the maximum yield for low-yielding wells that are computed by multiplying the available drawdown by the specific-capacity value may contain large errors if the wells were pumped at low rates that do not cause much water-level drawdown. The estimates of yield are likely to be too large because the effects of lowering the water level in the well below water-yielding zones have not been incorporated. Better yield estimates can be made by the use of step drawdown tests or by overpumping at a rate large enough to dewater most of the wellbore. The maximum well yield, after over pumping, can be estimated from the rate of water-level recovery or by subtracting the incremental rate of change of borehole storage at the end of the test from the pumping rate.

The pumping tests indicated that the specific amplitude values were subject to change within ±25 percent if the tests were completed with a change in pumping rate or a change in pumping duration, significantly affecting the comparability of repeated tests.

5.5. Confined aquifers

A confined aquifer is a geological formation pressed between two layers of impermeable rocks from above and below. Therefore, this reservoir is not fed by water except through areas where the water storage layers are exposed on the surface of the earth. The water in this formation is under a pressure higher than the atmospheric pressure due to the accumulation of rock pressure above the reservoir layer. Therefore, the well water flows in this formation freely and the level of the well water rises higher than the level of the aquifer without the need for a water withdrawal pump. The water level measured in wells that penetrate confined reservoirs aquifers is called the piezometric level.

According to the internal report by the Directorate of Groundwater-Erbil (2021), the confined aquifer extends from the (W01and W06) north of the sub-basin within the northern sub-basin (Kapran) to the northeast of the Erbil central sub-basin and to the east of the (W09 and W10) towards the southeast of the basin (W07). This belt forms a crescent in the feeding areas of the Erbil Central Sub-Basin. It extends from the east of the basin towards the center of the basin and crosses (W03 and W04) until it reaches (W11, and W12), (Figure 5.17). By comparing the depth of the groundwater levels of the surface wells with the deep wells, it is noted that the depth of the groundwater in the shallow wells in those areas exceeds the depth of the deep wells, and this confirms the existence of the state of artesian in the east and north-east of the basin and in these areas leads to a rise in the level of groundwater when drilling deep wells.

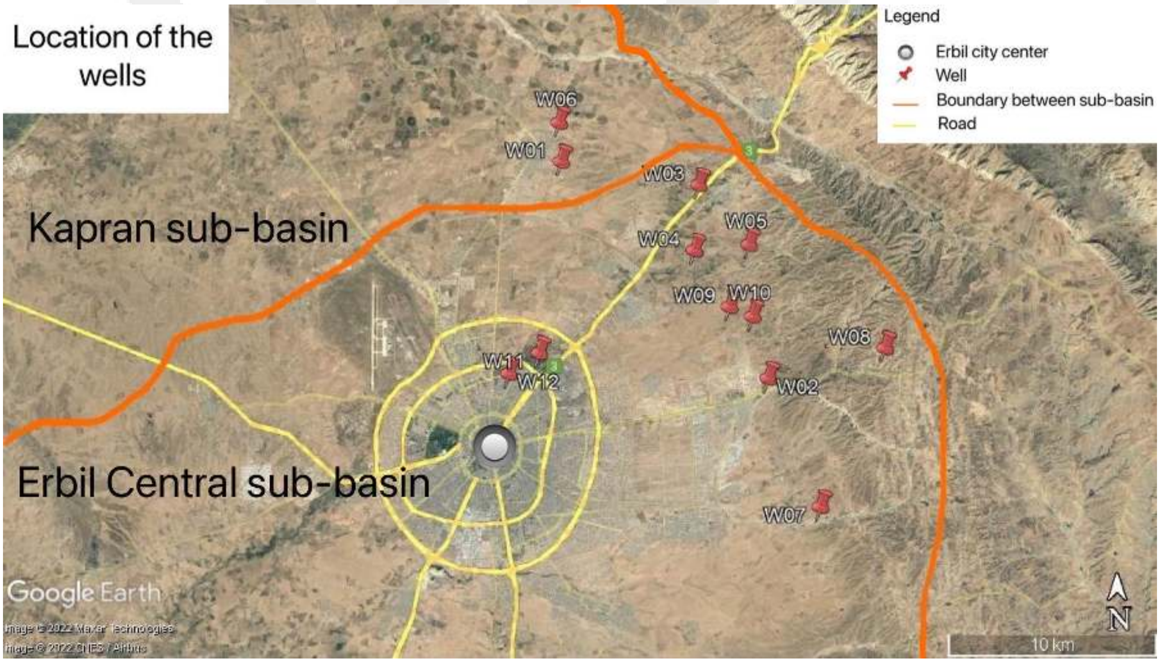

Figure 5.17. The locations of the 12 artesian wells recharging from confined aquifers in the Erbil Basin on a Google map.

As for the piezometric levels, the highest values are recorded in the northeastern and eastern sides of the plain, and the lowest values are recorded in the southwestern and western parts of the plain, which is expected due to the slope of the plain in general from the east towards the southwest and west, except for some areas in which Rarely, the piezometric levels, which are located to the west of the Erbil plain, are the result of the terrain elevation in the region, which raises groundwater levels in these areas. When comparing the results of the current survey with the piezometric map prepared by the internal report by the Directorate of Groundwater of Erbil (2021), it appears that the eastern regions of the plain have decreased their piezometric levels at a rate of approximately 26 to120 m (Table 5.6; Figure 5.18).

Table 5.6. Details about the 12 artesian wells of the Erbil Basin

No	Well Name	Initial Reading piezometric level (m)	Date(D/M/Y)	Last Reading piezometric level (m)	Date(D/M/Y)	Yield (g/m)	Depth (m)	Producing Formation	Aquifer Condition	GPS Coor. (UTM) X	GPS Coor. (UTM) Y	Elevation (m)
W01	Osman Mustafa yunis	artesian	20-01-2010	17.00	07-09-2021	45.00	171.00	Alluvium	Confined	414404	4018453	480.00
W02	Abd karim Omar Rasul	artesian	02-08-2009	31.00	17-09-2021	180.00	230.00	Alluvium+Bakhtiari	Confined	424237	4007801	663.00
W03	Latif Mustafa Taha	artesian	20-07-2009	30.00	28-09-2021	190.00	300.00	Alluvium+Bakhtiari	Confined	421080	4017189	417.00
W04	Shahram Rashid Abdu	artesian	03-09-2009	21.00	28-09-2021	130.00	230.00	Upper Bakhtiari	Confined	420799	4014018	606.00
W05	Abdu Al-Khalq Farhan	artesian	07-02-2011	50.00	28-09-2021	120.00	220.00	Alluvium+Bakhtiari	Confined	423436	4014245	716.00
W06	Nawroz	artesian	02-05-2010	26.00	07-09-2021	270.00	225.00	Alluvium	Confined	414337	4020349	487.00
W07	karim Osman Muhammad	artesian	29-04-2009	60.00	17-09-2021	85.00	297.00	Alluvium+Bakhtiari	Confined	426631	4001626	595.00
W08	Hussain Nadr Murad	artesian	03-08-2015	50.00	30-09-2021	75.00	288.00	Lower Bakhtiari	Confined	429840	4009166	740.00
W09	Kolaki Gawra	artesian	04-03-2009	48.00	28-09-2021	58.00	258.00	Upper Bakhtiari	Confined	422451	4011276	637.00
W10	Gule Ismail Ahmad	artesian	05-05-2010	52.00	29-09-2021	50.00	220.00	Upper Bakhtiari	Confined	423547	4010793	660.00
W11	Kwestan	artesian	22-09-2009	64.00	03-10-2021	75.00	300.00	Alluvium	Confined	413207	4009190	445.00
W12	Zanayan	artesian	07-04-2009	61.00	03-10-2021	80.00	400.00	Alluvium	Confined	411727	4008221	42400

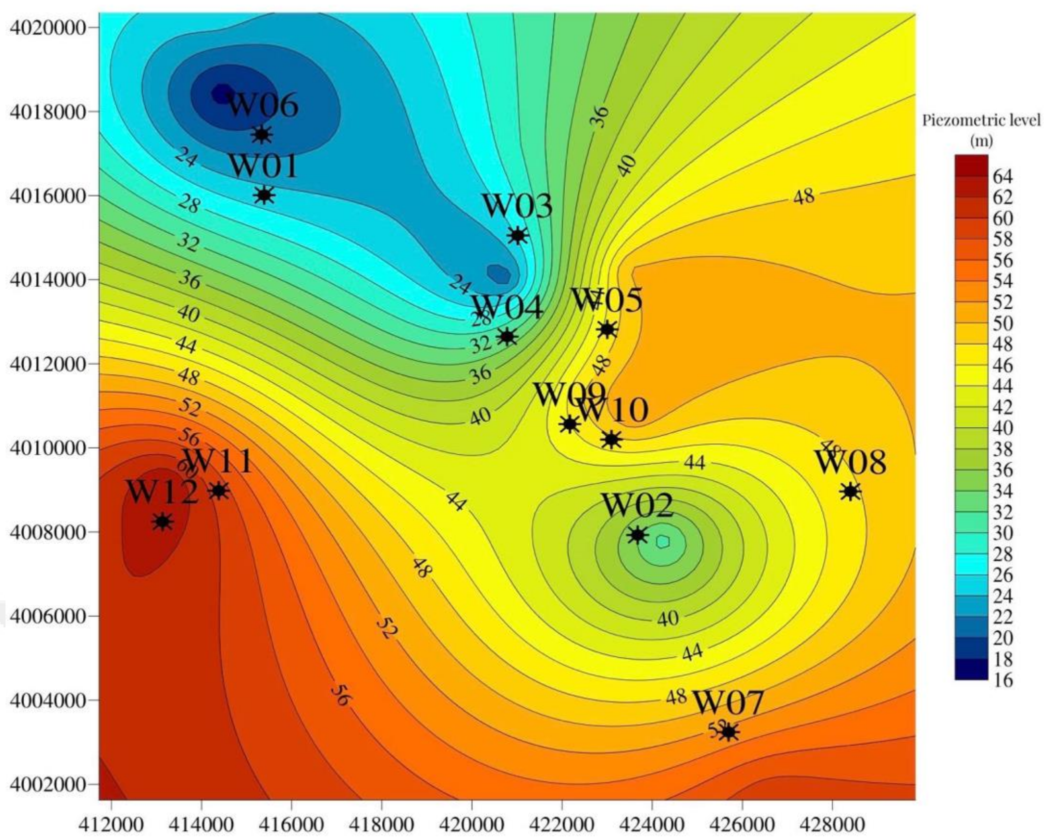

Figure 5.18. Piezometric map of the 12 artesian wells drilled in confined aquifers in the Erbil Basin.

6. GROUNDWATER LEVEL FLUCTUATIONS

Groundwater is not a constant. It is part of a dynamic flow system. It flows into and through aquifers from places with high water levels to places with low water levels. Groundwater level fluctuations caused by aquifer storage changes involve either the addition or extraction of water. Both naturally and through human intervention, and also climate change are the effects of groundwater level fluctuations. Climate change includes a decrease in precipitation, an increase in the number of hot days per year, and a change in the pattern of precipitation and rainy seasons on the other hand. Because of the ever-increasing demand, groundwater is regarded as an important natural resource in the study area. The efficient use of groundwater necessitates the ability to forecast resource fluctuations and, as a result, groundwater levels under various supply and withdrawal scenarios. Water table oscillations in unconfined aquifers can be caused by temperature changes and, when the water table is near the ground surface, evapotranspiration. All of these variables can influence how aquifer water levels fluctuate over time.

Long-term, seasonal, and short-term groundwater level fluctuations are used to monitor groundwater recharge and discharge. For a long time, computer programs processed the periodically observed groundwater level data from the assigned well (by the Directorate of Groundwater of Erbil) to show the long-term water table fluctuation and the general trend of groundwater level direction. The same procedure was followed for the seasonal groundwater level fluctuation for a specific year, with all observed data collected at the same time date in all observation wells to show the water table variation through groundwater elevation maps, seasonal flow nets, and to determine the amount of homogeneity of the aquifers and controlling subsurface structures. The fluctuation of the groundwater level is influenced by a variety of factors. Groundwater level fluctuations occur at various time scales, including long, seasonal, and short periods of time, as a result of various factors.

6.1. Time Variations of Levels

Level variation may be divided into three categories:

Secular Variations (Long term)

The long time periods of groundwater level fluctuations may be caused by a number of factors, the most important of which are:

1-It is undeniable that climate change has had a negative impact on the study area.

2- Variations in rainfall amount and pattern. It has an impact on the amount of recharge water entering the groundwater.

3- If there is a long period between two dry periods, rain-fed crops will absorb a large portion of the incoming rainstorms, reducing infiltrated rainwater percolation.

4- Changes in land use due to urbanization, industrialization, agricultural lands, and so on.

5- The dynamics of groundwater leakage as a natural phenomenon of groundwater flowing to adjacent basins or rivers

6- Excessive exploitation

Water level data was recorded from specialized wells to monitor the fluctuation of the groundwater level in the study area. Groundwater levels show erratic seasonal fluctuations with variations from 2001 to 2021 due to the mentioned factors. Between 2001 to 2021 the general long-term water level trend shows a rapid decrease in groundwater levels at different amounts of depths in different parts of the study area (Figure 6.1). It points out that the above-mentioned phenomenon as a whole has affected this deterioration general and especially climate change (Table 6.1). The increase in the number of drilling wells and over-exploitation of groundwater is the result of the development in various sectors in and around the study area. The decrease in the groundwater level in the study area varies from place to place (Table 6.2). They are visualized in a contour map (Figure 6.2; Figure 6.3). The maximum drop in the last twenty years was 111.3 m in Qushtapa well (W12). The lowest level in the Shorsh well (W19) was 15.02 m but according to the general trend line for these twenty years, the groundwater level fell by about 62.021 m (24 Wells).

Table 6.1. Total monthly precipitation in the study area (data were collected from Erbil meteorological station the year ranging from 2001 to 2021).

Year	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Sum
2001	85.00	42.60	96.50	35.70	12.40	0.00	0.00	0.00	2.20	4.40	19.60	28.90	327.30
2002	8.90	21.40	115.50	71.40	2.20	0.20	1.30	0.00	0.00	30.10	30.50	181.90	463.40
2003	60.90	69.20	99.60	43.90	16.40	9.10	0.00	0.00	0.00	15.90	81.00	100.30	496.30
2004	116.00	93.30	6.40	82.30	1.30	0.00	0.00	0.00	0.00	3.70	110.20	44.50	457.70
2005	75.60	84.10	50.70	26.10	17.30	0.00	0.00	0.00	4.20	4.80	15.30	19.40	297.50
2006	84.90	189.00	15.30	77.90	16.90	3.90	0.00	0.00	0.00	89.60	21.00	16.10	514.60
2007	55.50	98.60	39.00	49.10	15.60	1.40	0.00	0.00	0.00	0.00	5.30	8.90	273.40
2008	42.40	53.10	61.40	4.60	1.90	0.00	0.00	0.00	32.60	50.10	19.20	32.20	297.50
2009	1.60	29.00	88.70	28.60	0.00	5.50	0.00	0.00	10.10	26.50	16.30	105.60	311.90
2010	34.90	74.30	71.00	5.20	25.60	0.00	0.00	0.00	1.20	4.90	0.00	43.30	260.40
2011	113.90	42.80	30.50	101.50	12.70	0.00	0.00	0.00	0.00	9.20	7.40	25.00	343.00
2012	56.10	31.50	72.10	14.50	26.80	0.00	0.00	0.00	0.20	23.40	45.90	95.90	366.40
2013	174.40	55.80	17.70	37.40	40.60	0.00	0.00	0.00	0.00	0.20	19.10	86.60	431.80
2014	74.90	8.20	93.40	14.70	2.50	0.00	0.00	0.00	0.00	68.70	69.20	56.00	388.60
2015	37.40	44.30	56.80	17.30	5.40	0.00	0.00	0.00	4.50	36.40	104.40	115.80	422.30
2016	45.60	33.00	103.50	46.40	6.40	2.50	0.00	0.00	0.00	0.00	22.30	116.10	375.80
2017	37.90	23.40	77.80	55.80	4.40	0.00	0.00	0.00	0.00	0.00	37.60	29.40	266.30
2018	44.00	164.40	8.00	77.90	74.60	1.70	0.00	0.00	0.00	42.30	132.90	187.80	733.60
2019	119.10	64.20	220.10	123.50	5.40	0.70	0.00	0.00	0.00	19.30	3.90	45.80	602.00
2020	101.40	55.70	126.50	43.20	14.30	1.50	0.10	0.00	0.00	0.20	45.40	28.90	417.20
2021	40.00	24.60	27.80	0.30	3.40	0.00	0.00	0.00	0.00	4.40	4.00	91.70	196.20
Average													392.53

Table 6.2. The groundwater level variation in the monitoring wells in the study area for the period from 2001 to 2021(taking the difference from the recorded data and from the start and end of the trend line).

No	Well Name	Initial groundwater level (m)	Date(D/M/Y)	Current groundwater level (m)	Date(D/M/Y)	Difference between initial and current groundwater level (m)	Average (m)
W01	Qoritan Chukul	22.33	23-04-2001	76.80	28-09-2021	-45.77	
W02	Tandura /1	11.05	08-03-2000	77.20	28-09-2021	-66.15	
W03	Mastawa	12.96	23-04-2001	77.60	28-09-2021	-64.64	
W04	Shekh Sherwan	7.97	31-08-2000	72.90	28-09-2021	-64.93	
W05	Grd Azaban	9.50	08-03-2000	79.50	28-09-2021	-70.00	
W06	Perdawood	17.69	24-08-2000	69.70	28-09-2021	-52.01	
W07	Satoor-1	41.34	21-10-2006	115.80	07-09-2021	-74.46	
W08	Dugrdkan	19.85	28-04-2001	96.30	28-09-2021	-76.45	
W09	Murtka Shahab	24.15	21-04-2001	87.03	30-09-2021	-62.88	
W10	Bestanay Gawra	25.55	02-11-2004	86.08	30-09-2021	-60.53	
W11	Grd Mala-3	26.96	08-02-2000	90.30	30-09-2021	-63.34	
W12	Qushtapa-12	30.85	21-04-2001	142.15	30-09-2021	-111.30	
W13	Qultapa Yaba	34.33	22-04-2001	118.30	30-09-2021	-83.97	
W14	Nawroz-13	32.98	02-12-2004	94.40	07-09-2021	-61.42	
W15	Shadi-23	35.63	11-10-2005	139.60	07-09-2021	-103.97	
W16	Bakhe Shar Park	63.05	03-02-2004	79.40	30-09-2021	-16.35	
W17	C.science-1	51.98	12-02-2008	98.75	07-09-2021	-46.77	
W18	Bahar-4	36.7	11-10-2005	96.00	07-09-2021	-59.30	
W19	Shorsh-8	66.28	05-06-2004	81.30	06-09-2021	-15.02	
W20	Daratw-53	45.30	08-09-2000	134.55	30-09-2021	-89.25	
W21	Grda Rasha-4	41.20	20-06-2001	102.40	30-09-2021	-61.20	
W22	Shawais-10	33.62	08-02-2000	85.00	08-09-2021	-51.38	
W23	Kasnazan-7	87.90	08-12-2004	149.50	07-09-2021	-61.60	
W24	Sebirany Gawra	28.69	03-04-2001	54.50	20-09-2021	-25.81	- 62.02

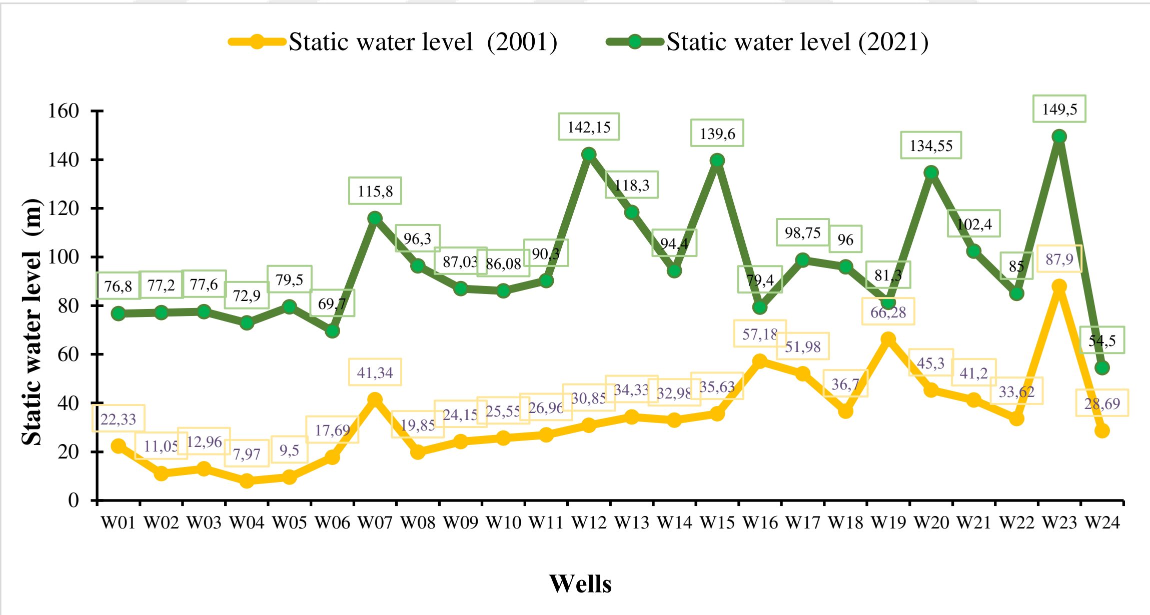

Figure 6.1. Comparison of static groundwater levels between 2001 and 2021.

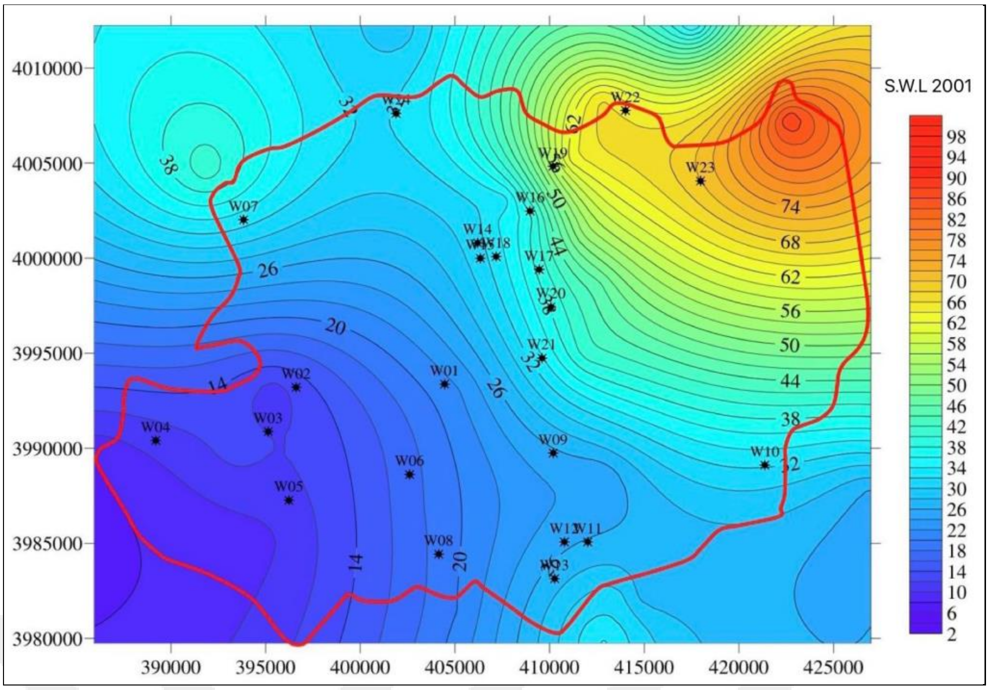

Figure 6.2. Contour map showing the variation of the depth of static groundwater level in 2001.

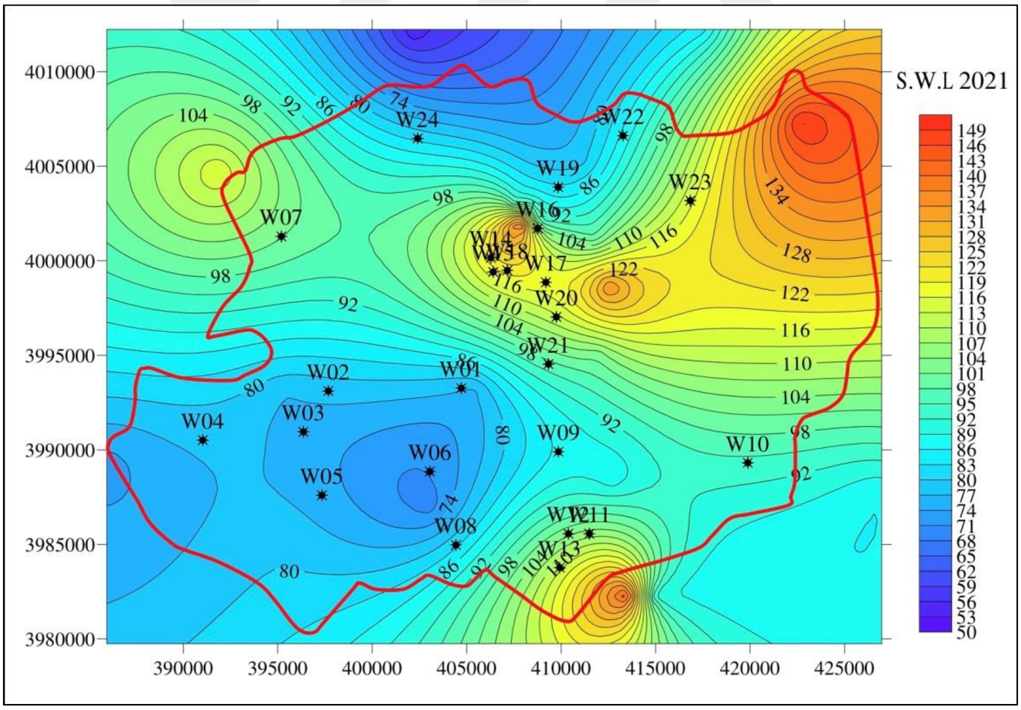

Figure 6.3. Contour map showing the variation of the depth of static groundwater level in 2021.

When comparing the annual average rainfall for the first period from 2001 to 2010, which amounted to 370 mm with the average annual rainfall for the second period from 2011 to 2021, which amounted to about 413 mm, the first period appears relatively dry compared to the second period (Table 6.1). However, the fluctuation of groundwater levels increased in the second period more than the first one in the study area, as the depth of groundwater levels increased in most areas in the Erbil Central sub-basin due to the decrease in rainfall in recent years (Figure 6.4),

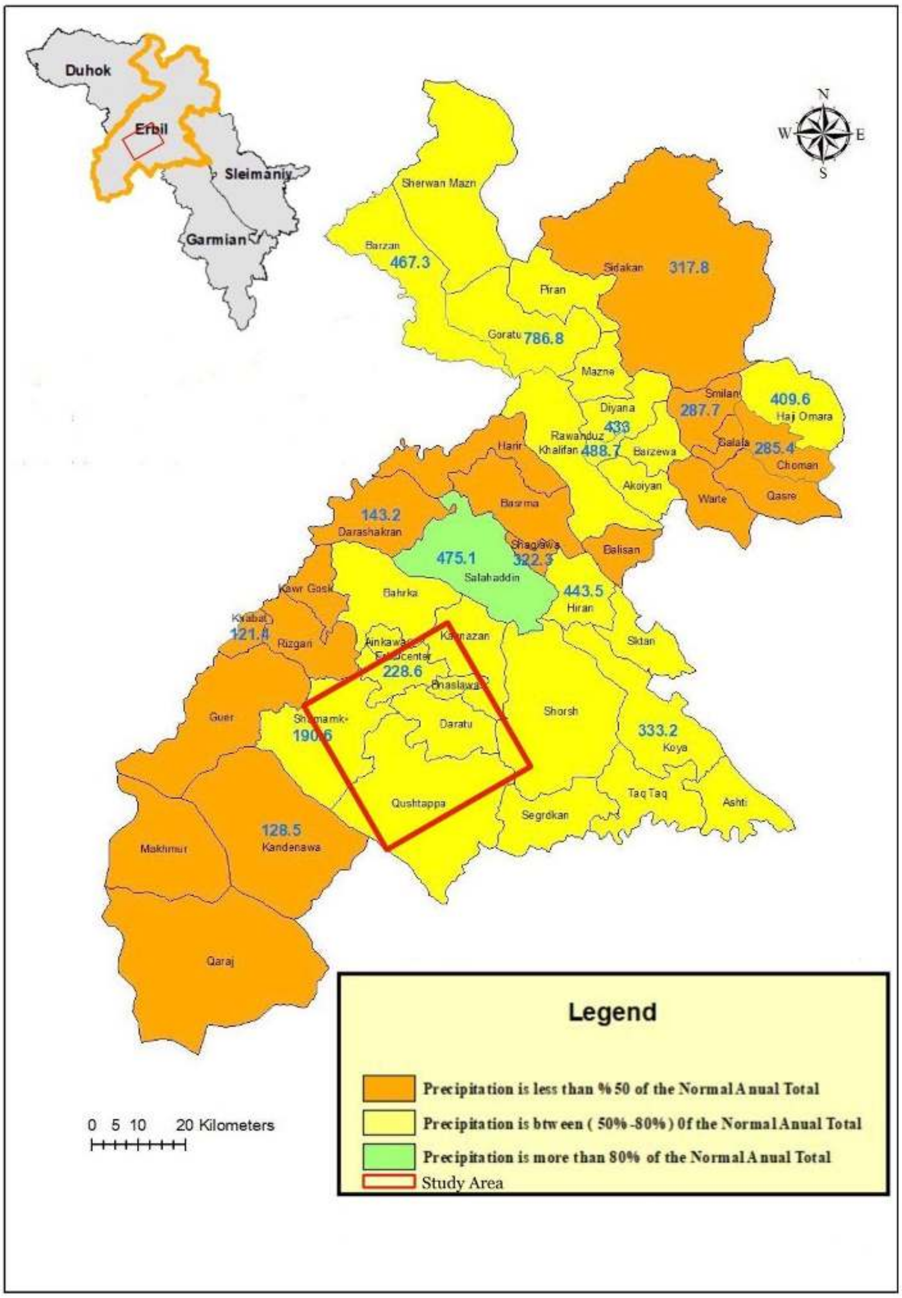

Figure 6.4. Map of the percentage of precipitation compared to the general total for the past years-Erbil city (General Directorate of Water Resources, 2022).

Changes in land use due to urbanization, industrialization, agricultural lands, the dynamics of groundwater leakage as a natural phenomenon of groundwater flowing to adjacent basins or rivers, and excessive exploitation could be the major sources for groundwater level fluctuations in study area. In the south of the Erbil central sub-basin including Qushtapa, Dugrdkan, Qultapa Yaba and Grd Mala regions the groundwater levels decreased between 63 to 111 m during the past twenty years (Table 6.2). In the same period, there was also a decrease in the groundwater level in the eastern and southeastern regions by more than 60 m, such as the areas in the east Kasnazan and Bestana (Figure 6.5). Furthermore, in the northwest of the basin, in the Sebirani Gawra, groundwater levels are decreased by 25.8 m (Figure 6.6). In the southwest of the sub-basin in areas Tandura, Mastawa, ShekhSherwan, groundwater levels are decreased (Figure 6.7). The groundwater levels also decreased by more than 66 m, and there was a decrease in the groundwater level in the north of the basin in the Shawais area, where the levels also decreased by more than 51 m. Decreasing of the groundwater level in the middle of the sub-basin in Qoritan Chukul is determined 45 m (Figure 6.8). Groundwater level drops detected in the wells in the city center of Erbil are between 15 m and 150 m (Figure 6.9). Main reasons for the decreasing in the groundwater levels of the aquifers in the Erbil Central sub-basin are increasing water demand due to increasing population, increasing number of drilling wells, and in addition to these factors, emergence of large areas of farms and factories that depend on groundwater in the region.

The creation of large agricultural lands and new zoning areas on the recharge areas of the central sub-basin prevents reaching of precipitation directly and fastly to the aquifers. Therefore, seeping of precipitation into the unconfined aquifers takes a long time, especially in the eastern part (=recharge area) of the study area. The effect of precipitation to the unconfined aquifers in the Erbil central sub-basin varies from east to west. The infiltration time of precipitation into the unconfined aquifers in the northeastern part of the sub-basin takes about 3 to 4 weeks, in the central part about 3 weeks, but in the western part it takes 2 to 3 weeks in the previous years (Qurtas, 2013). However, according to a current study of the Groundwater Directorate in Erbil, travelling of precipitation to the unconfined aquifers in the northeastern part takes 6 weeks, in the central part about 5 weeks, but in the western part it takes 3 weeks.

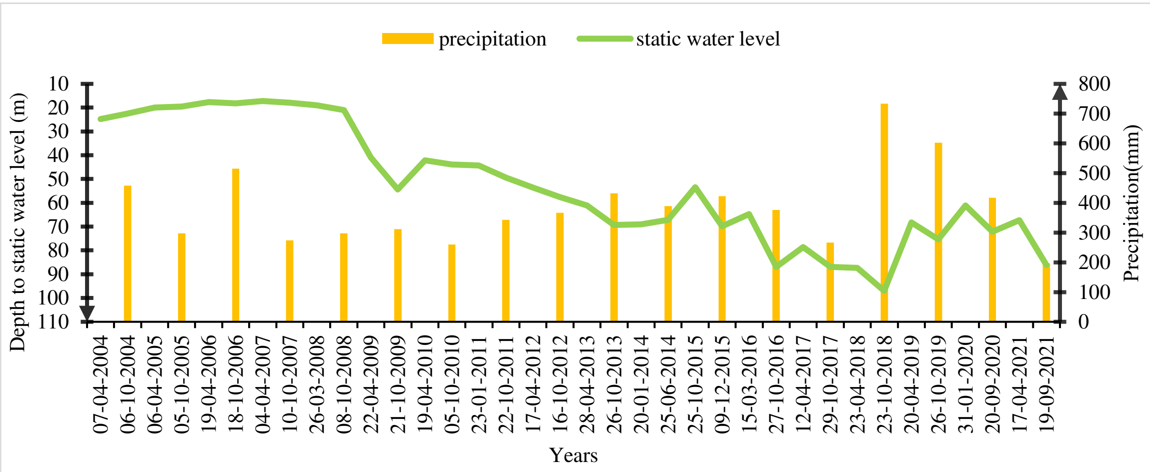

Figure 6.5. Long term groundwater level fluctuation between 07.04.2004 and 19.09.2021 (Bestanay Gawra well, W10).

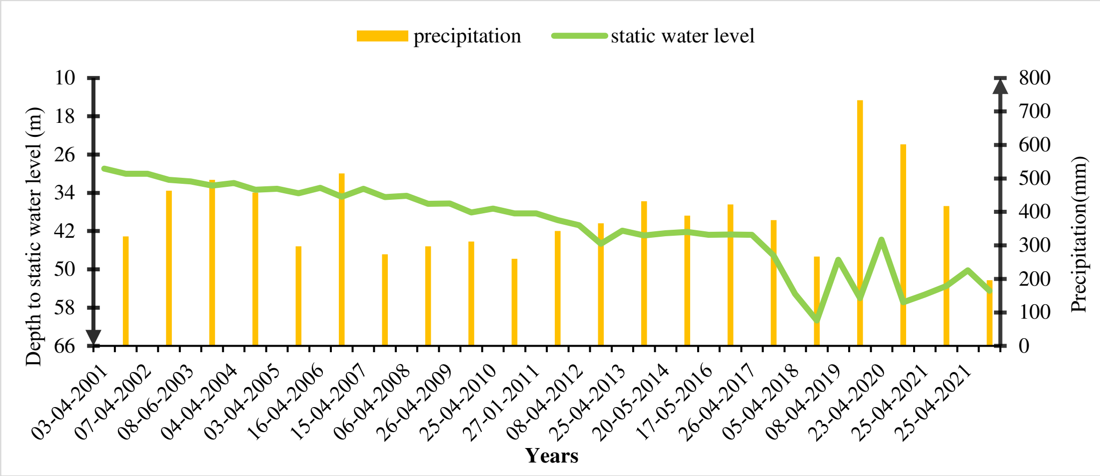

Figure 6.6. Long term groundwater level fluctuation between 03.04.2001 and 28.09.2021 (Sebirany Gawra well, W24).

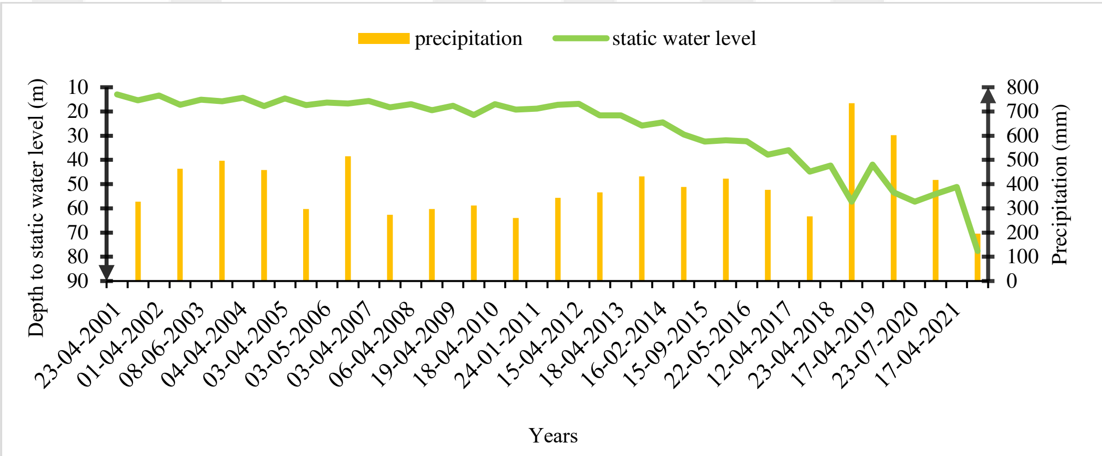

Figure 6.7. Long term groundwater level fluctuation between 23.04.2001 and 19.09.2021 (Mastawa well, W03).

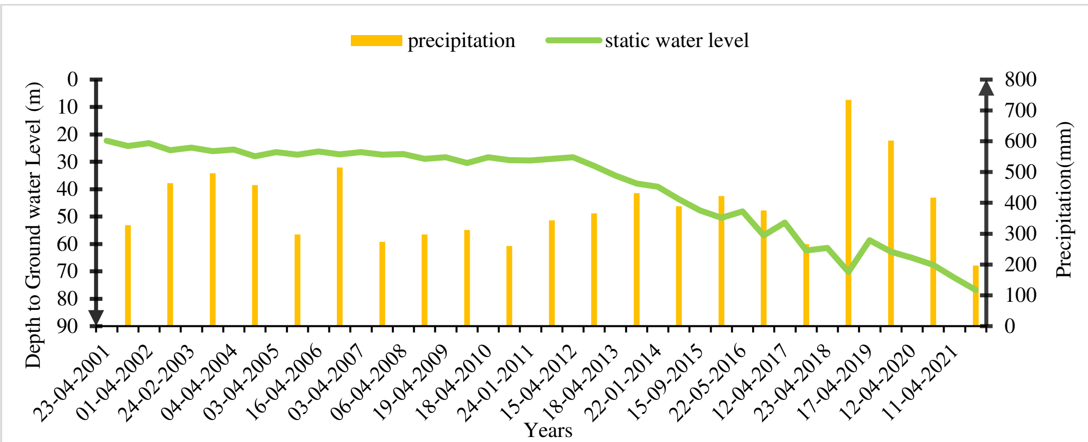

Figure 6.8. Long term groundwater level fluctuation between 23.04.2001 and 24.10.2021 (Qoritan Chukul well, W01).

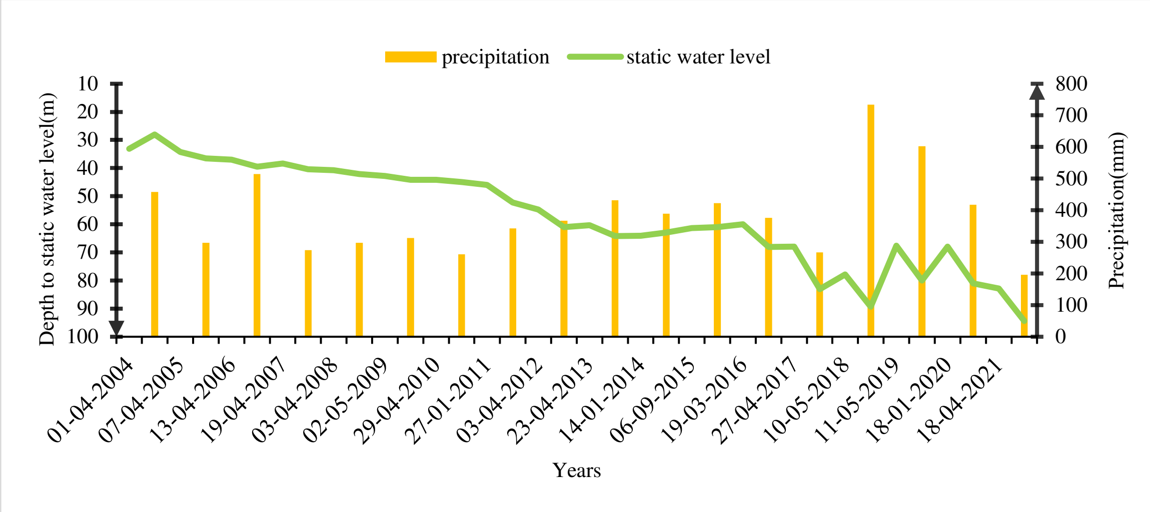

Figure 6.9. Long term groundwater level fluctuation between 01.04.2004 and 07.09.2021. (Nawroz well, W14).

Seasonal Variation

Under normal conditions, seasonal groundwater level variability is a balance of precipitation, evaporation, atmospheric pressure (for an unconfined aquifer), and irrigation. If the phenomenon of long-term groundwater level fluctuations is consistent, the season should be rhythmic and not change significantly in subsequent years. Because of the heterogeneity of water-bearing formations, topography, soil properties, and subterranean geological structures, seasonal groundwater level fluctuations should not be of the same magnitude everywhere. As a result, it influences the flow direction of groundwater. Rainfall is the most effective factor in controlling the seasonal fluctuation of groundwater and is the main source of groundwater recharge in the region. There is a big difference between groundwater levels in the wet year 2018-2019 and the dry period of 2020-2021 (Table 6.3). Water level data were recorded from specialized wells to monitor groundwater level fluctuations in the study area (Table 6.4). Groundwater levels show erratic monthly fluctuations with significant changes from year to year due to the change in the amount of precipitation.

Table 6.3. Total monthly precipitation in the study area during October, 2018-September, 2019 and during October, 2020- September, 2021 (data were collected from Erbil meteorological station)

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Sum (mm)
2018-2019	42.30	132.90	187.80	119.10	64.20	220.10	123.50	5.40	0.70	0.00	0.00	0.00	896
2020-2021	0.20	45.40	28.90	40.00	24.60	27.80	0.30	3.40	0.00	0.00	0.00	0.00	170.6

Table 6.4. The groundwater level variation in the monitoring wells in the study area for the period between October, 2020 and September, 2021

Well. No.	Wells Name	Depth of static water levels (m)											
		Oct.2020	Nov.2020	Dec.2020	Jan.2021	Feb.2021	Mar.201	Apr.2021	May.2021	Jun.2021	Jul.2021	Aug.2021	Sep.2021
W01	Qoritan Chukul	67.60	67.60	67.70	67.20	67.30	68.10	72.30	74.90	78.30	80.20	75.30	76.80
W02	Tandura /1	58.70	58.70	53.30	53.80	54.00	55.20	57.40	61.80	69.40	73.20	76.50	77.20
W03	Mastawa	63.20	63.20	54.1	54.20	54.40	55.90	51.20	52.80	59.30	61.20	76.20	77.60
W04	Shekh Sherwan	53.20	53.20	51.10	50.60	49.30	52.10	55.80	61.20	63.40	65.00	71.20	72.90
W05	Grd Azaban	70.90	70.90	64.8	64.2	63.90	65.20	61.90	57.30	71.50	73.70	79.00	79.50
W06	Perdawood	62.9	62.9	62.8	62.10	61.10	62.70	64.20	67.20	67.50	69.50	69.50	69.70
W07	Satoor-1	98.10	98.10	100.20	100.20	100.10	99.40	101.50	105.50	112.40	113.70	115.50	115.80
W08	Dugrdkan	78.30	78.30	82.6	82.30	81.00	81.80	82.80	85.00	87.20	90.10	95.00	96.30
W09	Murtka Shahab	74.70	74.70	73.70	73.90	74.34	75.98	77.10	80.85	81.71	84.15	84.65	87.03
W10	Bestanay Gawra	72.10	72.10	70.20	69.30	68.90	65.75.	67.30	71.80	78.12	81.17	83.80	86.08
W11	Grd Mala-3	79.41	79.41	71.95	72.20	72.69	74.25	76.50	79.96	83.00	85.10	87.22	90.30
W12	Qushtapa-12	131.00	98.15	99.20	93.40	110.70	124.60	134.20	131.80	130.98	133.63	138.28	142.15
W13	Qultapa Yaba	102.20	97.11	93	95.20	100.12	104.40	105.10	106.82	95.96	111.70	115.18	118.30
W14	Nawroz-13	81.00	88.50	88.35	86.50	80.90	81.10	82.80	85.16	88.40	88.60	94.35	94.40
W15	Shadi-23	110.60	110.00	108.00	106.00	102.60	99.80	102.20	104.70	125.40	128.00	139.40	139.60
W16	Bakhe Shar Park	74.20	73.10	72.40	72.30	73.40	73.53	74.80	75.60	77.30	76.60	77.65	79.40
W17	C.Science-1	95.45	96.10	95.80	95.60	95.00	95.20	97.10	98.20	98./50	98.55	98.80	98.75
W18	Bahar-4	92.20	93.20	86.30	86.10	85.80	85.60	86.50	88.40	89.80	92.05	96.25	96.00
W19	Shorsh-8	75.10	74.50	73.80	72.30	71.80	73.10	74.20	76.70	78.90	79.70	81.50	81.30
W20	Daratw-53	118.00	115.10	111.00	112.10	113.30	115.28	118.70	123.70	125.85	127.60	132.72	134.55
W21	Grda Rasha-4	104.95	102.55	94	97.50	102.12	99.72	102.40	106.80	107.30	106.60	101.70	102.40
W22	Shawais-10	82.50	83.40	79.20	78.70	77.30	77.10	78.90	83.20	85.10	85.00	85.10	85.00
W23	Kasnazan-7	110.20	141.20	141.20	141.10	141.10	146.10	146.70	147.40	147.80	148.45	149.40	149.50
W24	Sebirany Gawra	53.50	49.90	49.10	48.70	49.9	49.74	50.20	51.75	51./85	52.45	54.20	54.5

The highest negative fluctuation values appeared in the eastern parts of the basin (Kasnazan Well numbered as W23). The groundwater level depth is decreased from 110 m to 141m from October, 2020 to December, 2020 whereas it is decreased, and from depth 141.1 m to 149.5 m from February, 2021 to September, 2021 which is normal due to little amount of precipitation (Figure 6.10). The direction of groundwater flow is generally from the east to west in the Erbil Central sub-basin. This situation, leads to a rapid decline i, In groundwater levels in areas where there are relatively high groundwater levels. While from October, 2018 to June, 2018 the positive volatility is from a depth of 93.4 m to 90.7 m. This explains the difference between these two periods and the reason is due to the increased amount of precipitation in the region (Figure 6.10).

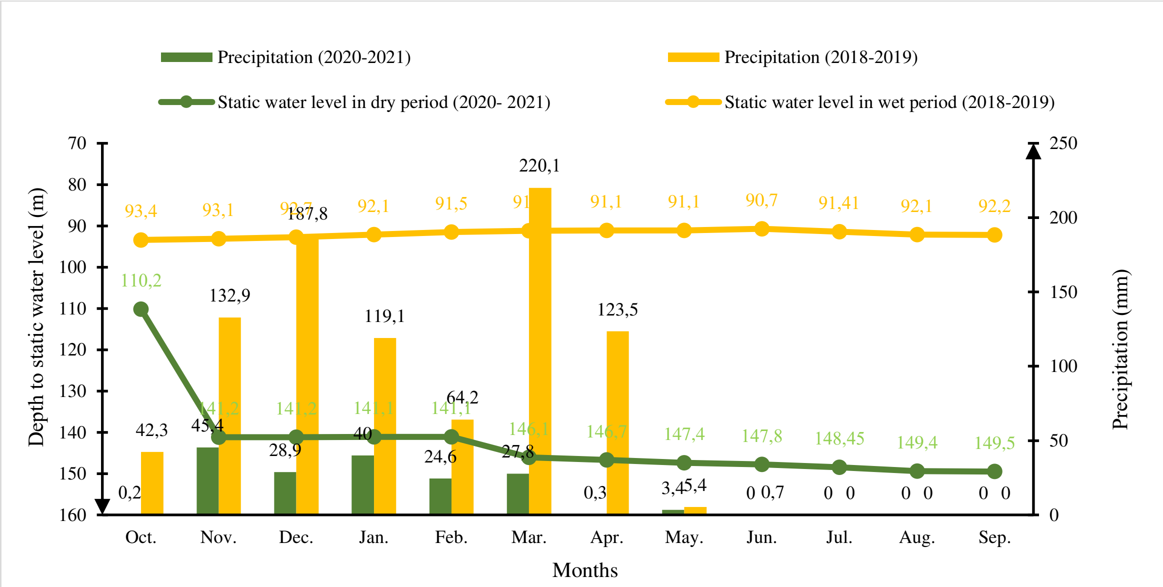

Figure 6.10. Comparison of groundwater level and precipitation in 2018 - 2019 and 2020 - 2021) (Kasnazan well, W23).

The negative oscillation values appeared in the southeastern parts of the basin (Bestanay Gawra well, W10) from a groundwater level depth of 72.1 m to 44.8 m from October 2020 to March 2021, while from October 2018 to February 2019, the positive groundwater level oscillation was from the depth of 97 m to 45 m (Figure 6.11). The great difference between these two periods, is due to the increase in rainfall, the type of aquifer, and the movement of groundwater from east to west. According to the study of the Groundwater Directorate in the region in 2004, the depth of the groundwater level wells located at the eastern and southeastern sides of the Central sub-basin of Erbil is much less than the depth of groundwater level in deep wells. This is an indication of the presence of perched aquifer in some eastern and southeastern parts of the sub-basin (Figure 6.11).

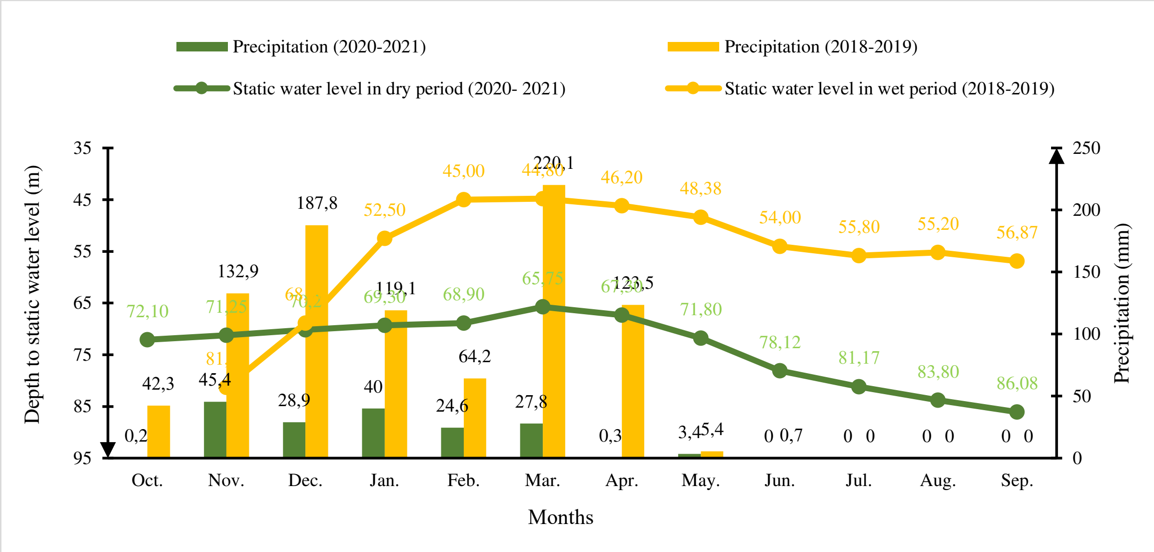

Figure 6.11. Comparison of groundwater level and precipitation in 2018 - 2019 and 2020 - 2021 (Bestanay Gawra well,W10).

The highest negative fluctuation values appeared in the southern parts of the sub-basin (Qushtapa well, W12) from 93.4 m to 134.2 m from January 2021 to April 2021 (dry year), while there was a positive fluctuation from 96.3 m to 87.52 m from November, 2018 to May, 2019 (Figure 6.12). The reason for the groundwater level fluctuation in W12 is due to the amount of rainfall and the presence of large areas of factories and farms that depend only on deep wells in the dry periods (from June to October) in the region (Figure 6.12).

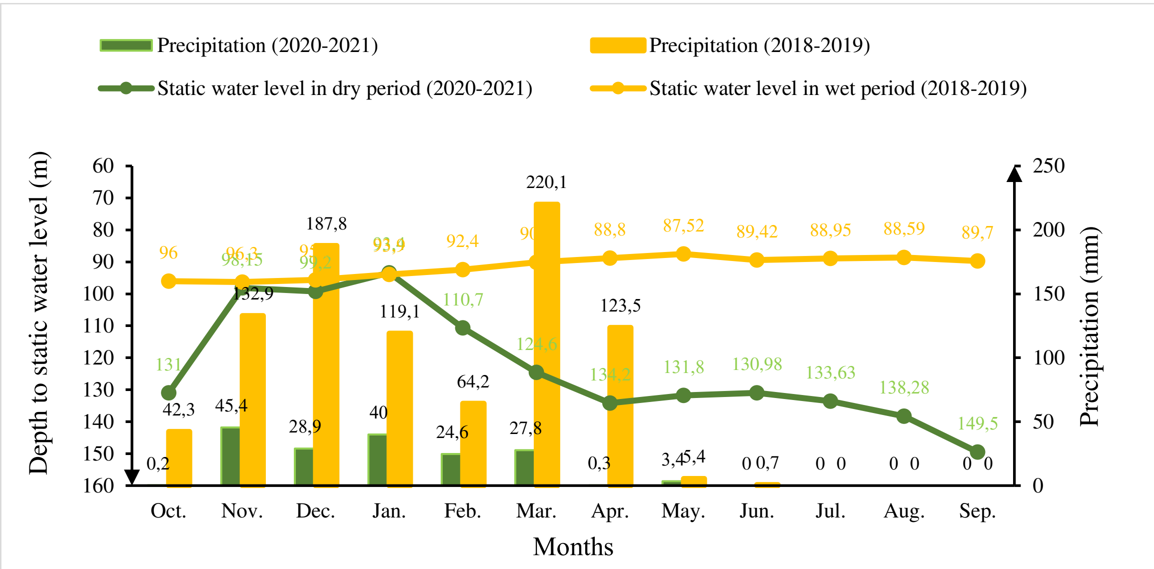

Figure 6.12. Comparison of groundwater level and precipitation in 2018 - 2019 and 2020 - 2021) (Qushtapa well, W12).

The highest values of negative oscillation appeared in the southwestern parts of the basin (Shekh Sherwan well, W04) from a depth of 49.3 m to 72.9 m from February 2021 to September 2021 (dry period), while from October 2018 to May 2019 (wet period), the positive oscillation is determined from depth 43.8 m to 29.89 m. The reason for the groundwater fluctuation in W04 is due to the change in the rate of precipitation, the movement of groundwater flow from the eastern and central regions towards southwestern of the sub-basin, and, the leakage of irrigation water (Figure 6.13).

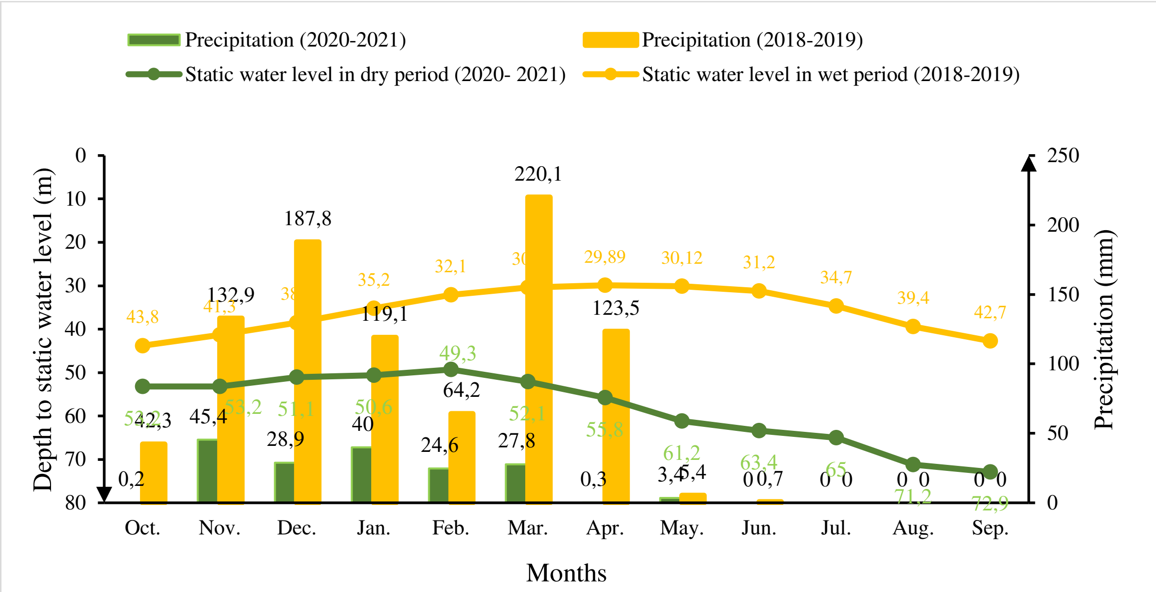

Figure 6.13. Comparison of groundwater level and precipitation in 2018 - 2019 and 2020 - 2021) (Shekh Sherwan well, W04).

The highest values of negative oscillation appeared in the western parts of the sub-basin (Satoor well, W07) from a depth of 98.10 m to 149.5 m from October 2020 to September 2021 (dry period), while the depth is from 59.6 m to 31.25 m from October 2018 to July 2019 (wet period) (Figure 6.14). The reasons for this rapid deterioration in the groundwater level in W07 are; the percentage of rainfall, the characteristics of the geological formation in the area (Lower Bakhtiary Formation) and, the movement of groundwater from that area to the Great Zab River.

Abnormal fluctuations that sometimes notices are due to the pump malfunction in that period, (Figure 6.14).

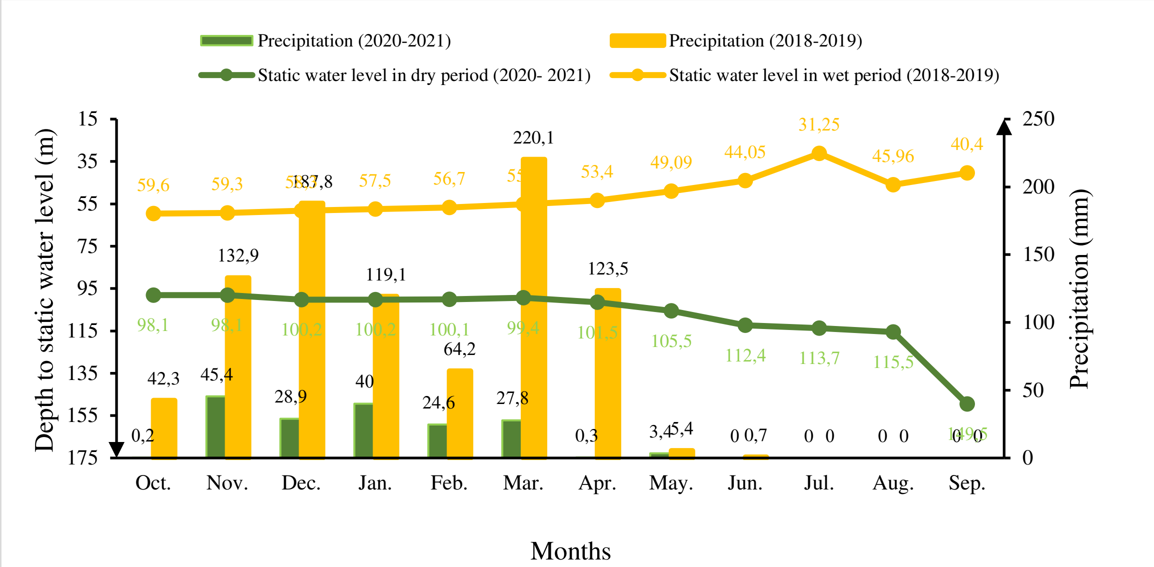

Figure 6.14. Comparison of groundwater level and precipitation in 2018 - 2019 and 2020 - 2021) ((Satoor well, W07).

The highest values of negative fluctuation appeared in the northern and northwestern parts of the sub-basin in Sebirany Gawra well (W24) from 49.74 m to 54.50 m from March 2021 to September 2021 (dry period), while the positive groundwater level fluctuation (from the depth 56 m to 48.8 m) is determined from October 2018 to March 2019 (wet year). The major reason for the groundwater level fluctuation in W24 is the amount of precipitation fall in this area (Figure 6.15).

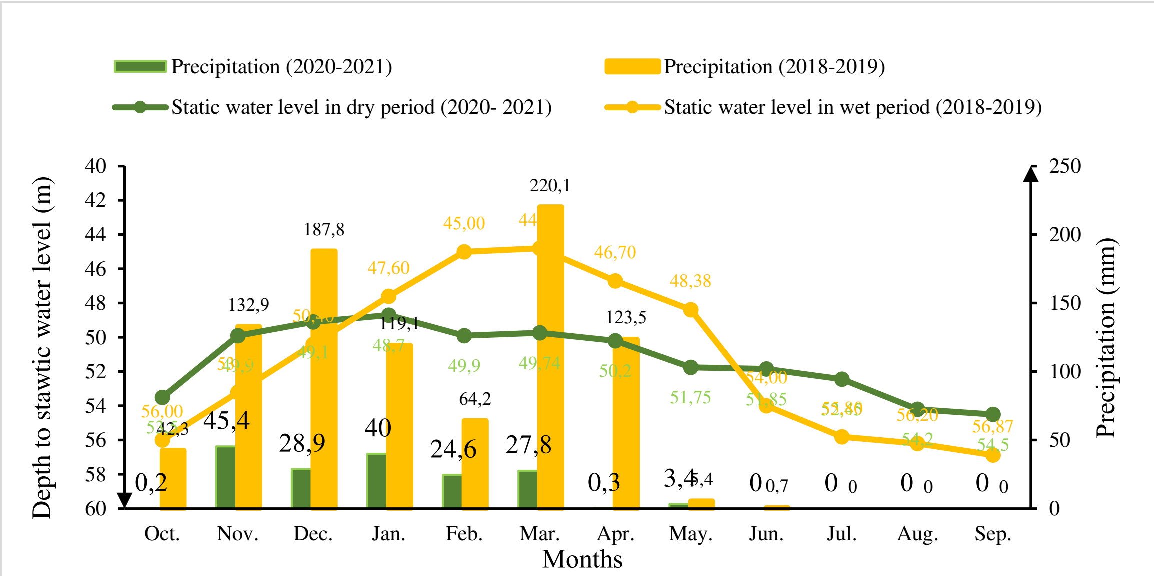

Figure 6.15. Comparison of groundwater level and precipitation in 2018 - 2019 and 2020 - 2021 (Sebirany Gawra well, W24).

The negative fluctuation values were determined in the center of Erbil city in (Nawroz well (W13) from a depth of 80.90 m to 94.40 m from February 2021 to September 2021 (dry period), while the positive fluctuation was determined from a depth of 89.36 m to 66.60 m from October 2018 to December 2018 (wet year) (Figure 6.16). The groundwater level fluctuation (especially the decrease of the groundwater level) that was determined between these two periods is due to the lack of groundwater recharge during the drought years, the absence of groundwater movement from the eastern part of sub-basin towards the center of the sub-basin, and the excessive consumption of groundwater by the people of the region (Figure 6.16).

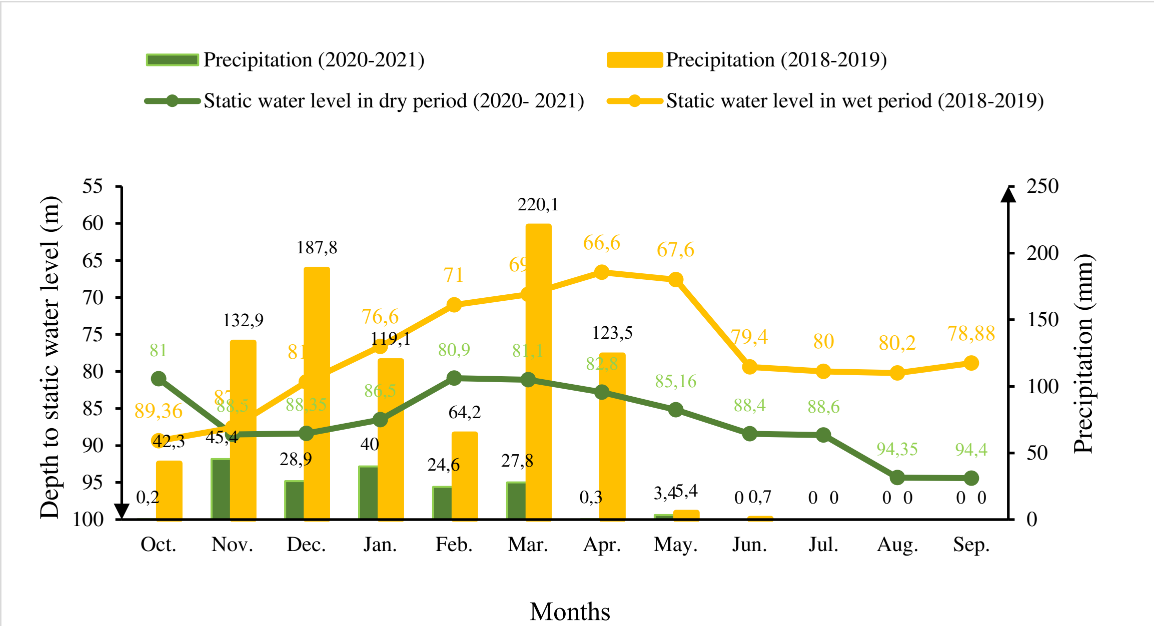

Figure 6.16. Comparison of groundwater level and precipitation in 2018 - 2019 and 2020 - 2021) (Nawroz well, W13).

The negative oscillation values were determined in the center of the sub-basin in (Qoritan Chukul well (W01) from 67.20 m to 80.20 m from January 2021 to July 2021 (dry period), while from October 2018 to May 2019 (wet period), the positive oscillation was determined in W01 from 70.2 m depth to 58.32 m (Figure 6.17). The lack of rainfall, the lack of groundwater recharge during the drought years, the absence of groundwater movement from the eastern of sub-basin (from the recharge area), to the center of the basin, and the high consumption of groundwater for agricultural and industrial purposes, leads to a decrease in the groundwater level in this area (Figure 6.17)

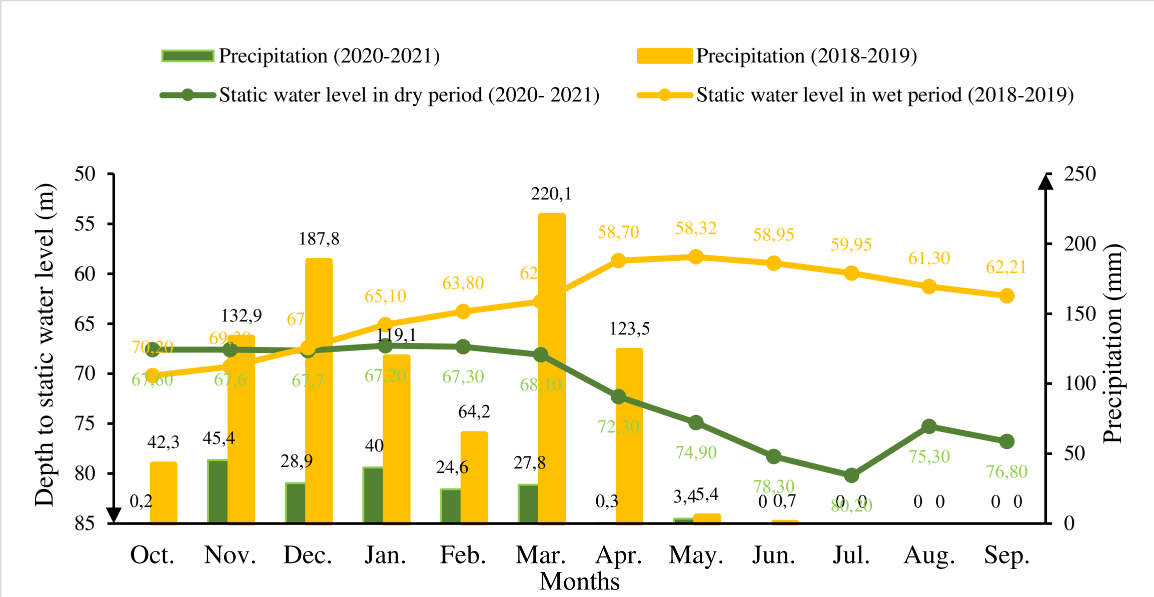

Figure 6.17. Comparison of groundwater level and precipitation in 2018 - 2019 and 2020 –2021 (Qoritan Chukul well, W01).

The groundwater level fluctuations during the four seasons (autumn, winter, spring, summer) in the study area are completely variable (Table 6.5; Figure 6.18).

Table 6.5. Variation in the groundwater level in the investigated wells in the study area for the four seasons (from October, 2020 to September, 2021)

Well No.	Wells Name	Static Water Level (2020-2021)			
		Autumn	Winter	Spring	Summer
W01	Qoritan Chukul	67.50	67.40	71.77	77.93
W02	Tandura /1	58.60	53.70	58.13	73.03
W03	Mastawa	63.10	54.23	53.30	65.57
W04	Shekh Sherwan	53.05	50.33	56.37	66.53
W05	Grd Azaban	70.80	64.30	61.47	74.73
W06	Perdawood	62.75	62.00	64.70	68.83
W07	Satoor-1	97.95	100.17	102.13	113.87
W08	Dugrdkan	78.05	81.97	83.20	90.77
W09	Murtka Shahab	74.50	73.98	77.98	83.50
W10	Bestanay gawra	71.95	69.47	69.55	81.03
W11	Grd Mala-3	79.31	72.28	76.90	85.11
W12	Qushtapa-12	114.58	101.1	130.20	134.30
W13	Qultapa Yaba	99.66	96.11	105.44	107.61
W14	Nawroz-13	84.75	85.25	83.02	90.45
W15	Shadi-23	110.3	105.53	102.23	130.93
W16	Bakhe shar park	73.65	72.70	74.64	77.18
W17	C.science-1	95.78	95.47	96.83	98.68
W18	Bahar-4	92.70	86.07	86.83	92.70
W19	Shorsh-8	74.80	72.63	74.67	80.03
W20	Daratw-53	116.55	112.13	119.23	128.72
W21	Grda rasha-4	103.75	97.87	102.97	105.20
W22	Shawais-10	82.95	78.40	79.73	85.07
W23	Kasnazan-7	125.70	141.13	146.73	148.55
W24	Sebiran Gawra	51.70	49.23	50.56	53.33

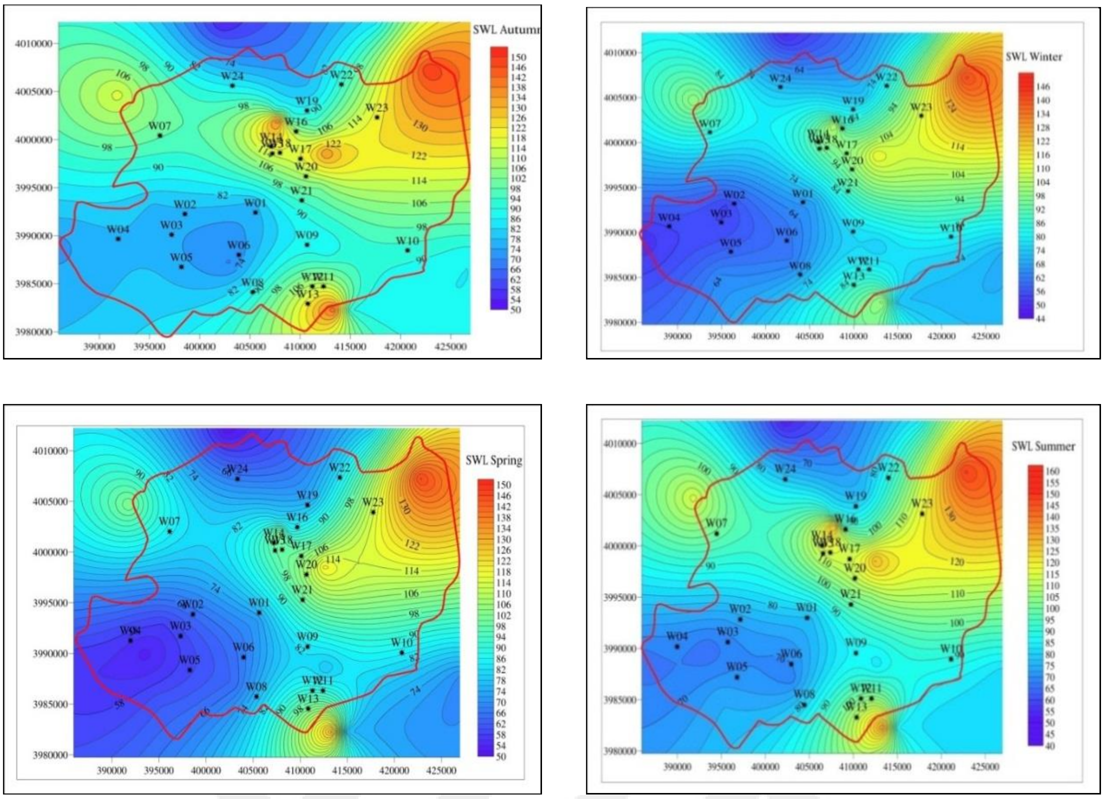

Figure 6.18. Contour maps showing variation of groundwater level fluctuation for the four seasons (from October, 2020 to September, 2021).

Short term

Groundwater levels are frequently subject to short-term changes that are influenced by the major usage of groundwater in a given area. Clearly defined diurnal variations may be associated with municipal water supply wells. Similarly, weekly patterns occur with pumping for industrial and municipal purposes (Figure 6.19).

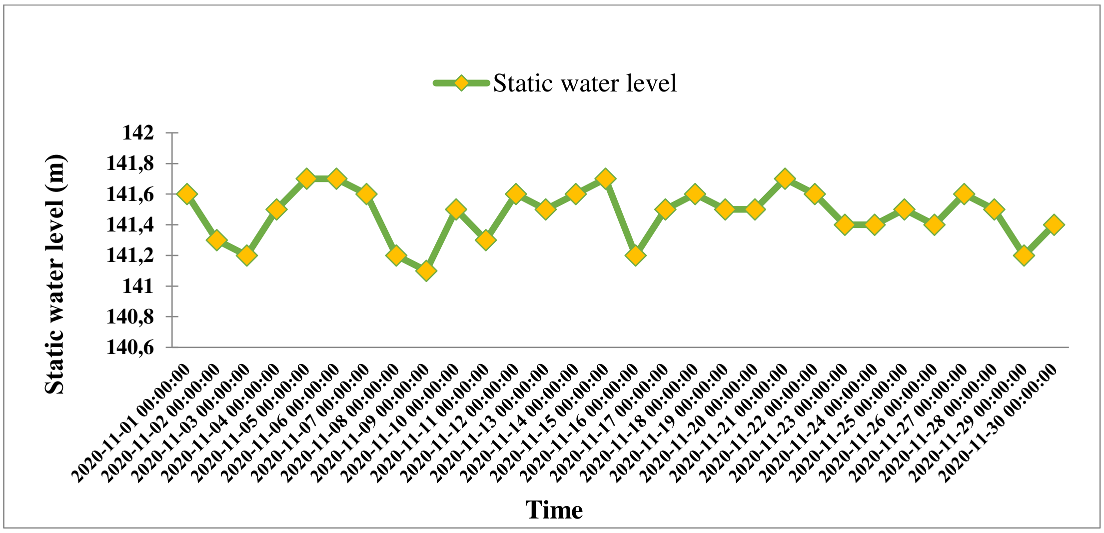

Figure 6.19. Distinctive short-term fluctuations in groundwater levels accompany specific daily variations.

6.2. Evaporation

Evaporation from groundwater increases as the water table approaches the surface of the earth. The rate is also influenced by the soil structure, which regulates capillary tension and consequently hydraulic conductivity above the water table. The results are expressed as a percentage of evaporation at the Earth's surface. For streams located at a distance of one meter from the surface of the earth, evaporation is largely controlled by atmospheric conditions, but under these soils the property becomes limited and the rate decreases markedly with depth. Accordingly, there is no effect of evaporation on the fluctuation of the groundwater level in the study area as a result of the large depth of the groundwater level from the surface (Figure 6.20).

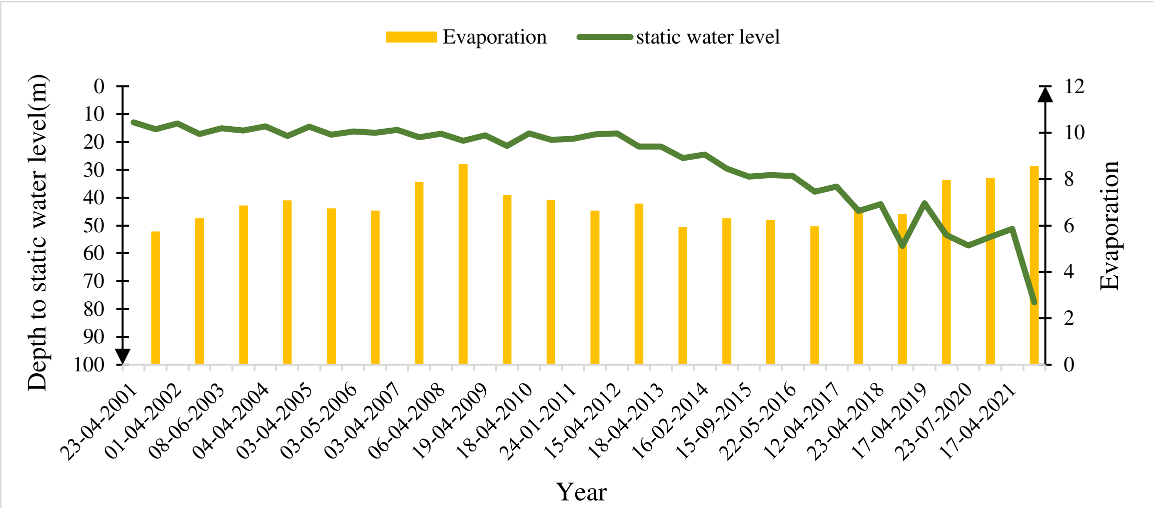

Figure 6.20. Comparison between static water level and evaporation for showing the effect of evaporation on the variability of the groundwater level during the period from 2001 to 2021 (Mastawa well, W03).

6.3. Surface water

When a stream channel comes into direct contact with an unconfined aquifer, the unconfined aquifer may be recharged or discharged into the stream. The flowing Greater Zab River receives water from the surrounding unconfined aquifer, while "lost rivers" seep into the underlying aquifer, according to the internal report by the Directorate of Groundwater of Erbil (2021) (Figure 6.21).

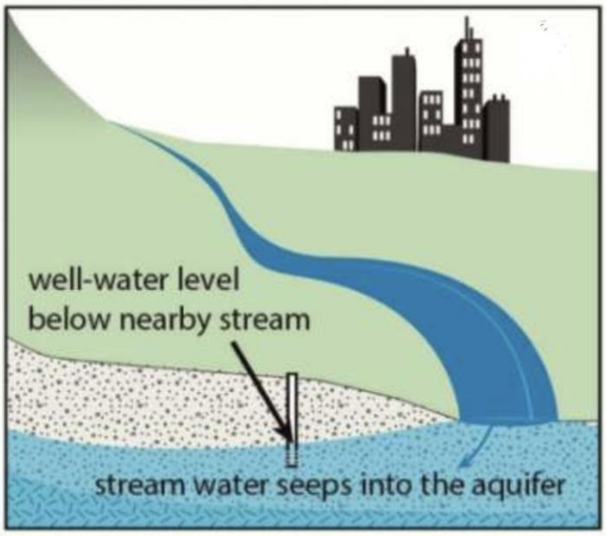

Figure 6.21. Recharging of the aquifer from the stream water (URL 1).

Three wells were studied in the present study, to show that the groundwater level was lower than the nearest stream in the al-Kalak area, west of Erbil city (Table 6.6; Figure 6.22). This creates a gradient that can push water from the river channel into the aquifer below as shown in Kaurgosk and Sufaiya (North and South Kalak provinces), too. They noted that rivers are particularly prone to water loss in arid regions, along with flat terrain and in areas where groundwater is pumped on a large scale, and the study also showed in the region that the general flow of groundwater is heading towards the Great Zab River and partly towards the Khazr River, which is the main area of groundwater drainage in the western part of this area, and water levels fluctuate over the years and decades, indicating that groundwater typically fluctuates by no more than a few meters throughout the year. However, the water level in many wells near lost rivers was more than five meters below the surface of the nearest stream, increasing confidence that the river's flow was It can spread widely.

Table 6.6. Information for the 3 selected wells near the Greater Zab Rriver.

Point No.	Well Name	GPS Coor. (UTM)X	GPS Coor. (UTM)Y	Elevation (m)	Static w.l 17 May 2021 (m)	Water table 17 May 2021 (m)
Point 1	River edge 1	378122	4014611	243.00	-	243.00
Point 2	River edge 2	377613	4014145	243.00	-	243.00
Point 3	Mashtal Well	379080	4015379	245.00	12.20	232.80
Point 4	Happy Park Well 1	378245	4014109	246.00	5.80	240.20
Point 5	Happy Park Well 2	378227	4013867	245.00	5.70	239.30

Figure 6.22. The location of the 3 wells near the Greater Zab River, west of the Erbil Central Sub-Basin on the Google Map.

Therefore, rivers and seasonal streams contribute to the fluctuation of groundwater in the study area. The effect of seasonal currents when crossing a long route to the outlet is noticeable, but not quantified, which was considered in this study with leakage feeding. Another recharge is suggested in this area, namely seepage from the Greater Zab, Lesser Zab, and Wadi Bastoura through formations, joints, and fissures.

6.4. Urbanization

Changes in groundwater levels are frequently caused by the urbanization process as a result of reduced recharge and increased withdrawal. In recent years, it has seen significant changes in land use (primarily urbanization). The findings are consistent with many previous studies that have highlighted the significant increase in urban growth and its impact on runoff infiltration and production, thus on groundwater (Figure 6.23).

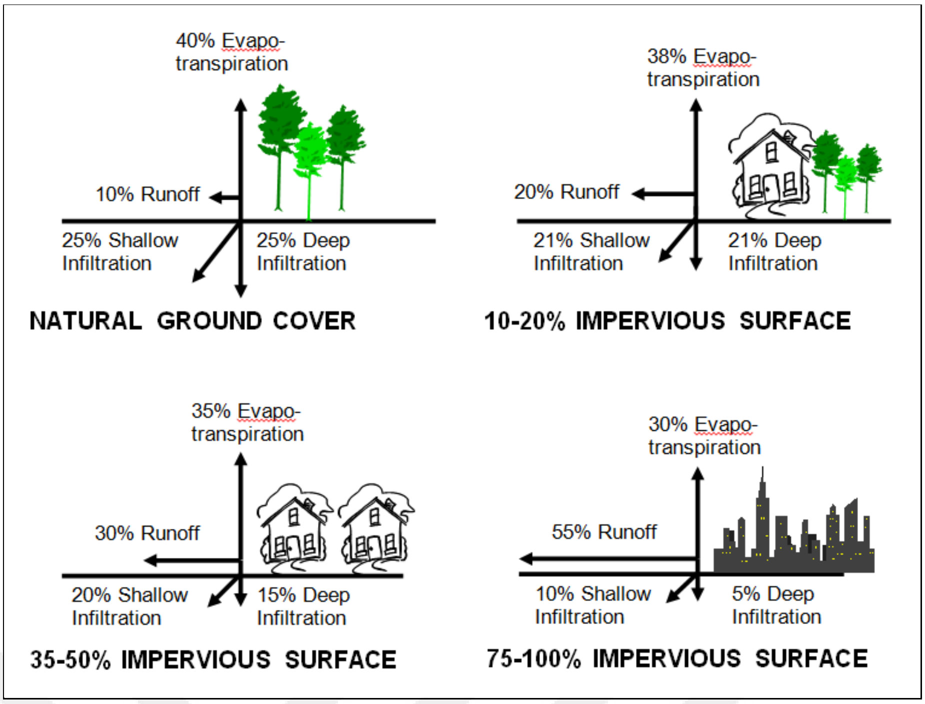

Figure 6.23. Impact of impervious area on the hydrologic cycle fluxes (adapted from Prince Georges County Department of Environmental Resources Programs and Planning Division, 1999).

Between 1984 and 2014, agricultural land and vegetation cover decreased, while untapped areas and barren soils increased. Furthermore, the increase in the built-up area may cause obstructions in the drainage network, resulting in a variety of environmental issues such as flooding. According to the current study, urban expansion has resulted in the reduction or removal more than of 28% of the drainage network in the Erbil Central Sub-Basin. Urbanization rose three times faster than population growth by 95 percent between 2004 and 2014, demonstrating that average land growth outpaces population growth (Faqe and Hashemi, 2015).

Other research suggests that the watershed's topography may also play a significant role in increased storm runoff. as shown in Figure 6.24. The obtained results were classified into three categories. The first category represents values less than one, indicating a decrease in runoff depth due to the expansion of agricultural and vegetable land, whereas the second area represents no change in runoff depth from 1984 to 2014. Category III refers to an increase in runoff depth caused by a change in land cover to impermeable areas and barren soils. According to the study, 71% of the Erbil Central Sub-Basin falls into the third category. These changes will have a direct impact on flood risk, particularly because the central Erbil Basin dominates the lower part of the watershed.

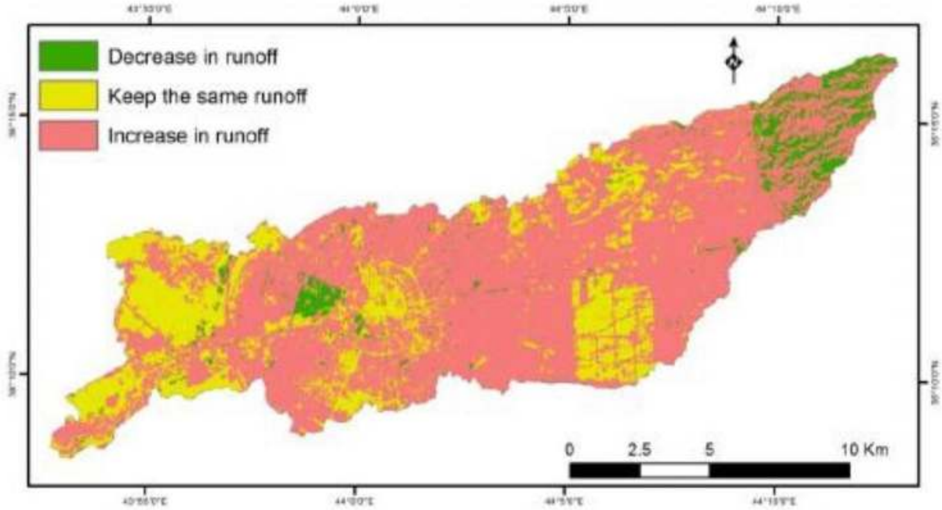

Figure 6.24. Runoff volume changes from 1984 to 2014 (Faqe and Hashemi, 2015).

7. CONCLUSIONS

The basin is mostly covered by Quaternary deposits, with Upper Bakhtiari and Lower Bakhtiari Formations. The productive aquifer is thought to be around 500 m thick, with Quaternary deposits averaging 350 meters thick in the middle of the basin. The basin was most likely formed by subsidence as step sliding by faults striking NW - SE in the east and west, as well as by faults striking NE - SW in the north and south. Potential evapotranspiration calculated by Thornthwaite, Blany-Kriddle, and Kharrufa methods are 1577.26 mm, 2081.98 mm, and 2237.48 mm respectively. The water surplus and water deficit are 58.36 mm and 1951.40 mm respectively. The period of water surplus is from December to February and the period of water deficit is from March to November. The soils of the Erbil Central sub-basin are of mixed type, with grain sizes ranging from fine clay to coarse sand, so the soil is classified as class A according to the classification proposed by the Soil Conservation System method. As a result, the curve number for this soil condition is 65. The pumping test and data analysis revealed that the dominant system is an unconfined system, with confining beds found locally and vertically in some depths, forming a local confined aquifer. Most time-drawdown plots behaved like leaky aquifers, but this was due to leakage from different depths in the well column through the gravel pack and screen, as well as reaching the recharge boundaries' drawdown. The transmissivity ranged from 0.52 to 183.3 m^2/d, the specific yield ranged from 0.088 to 0.281, the hydraulic conductivity is between 0.0027 to 1.1315 m/day, the specific capacity ranged from 0.85 to 318.31 m2/d/m, and, the storage coefficient is between 0.0128 to 6.386. There is a great relationship between precipitation and the fluctuation of the groundwater level, as the leaching factor from rainwater affects the recharge of groundwater, so the groundwater level rises whenever the amount of water infiltrated into the ground increases. Long-term groundwater level fluctuation declined to an average of (from 2001 to 2021) 62 meters, it is ranged between 15 m to 111.3 m. The seasonal groundwater level fluctuation showed not much change in water table and pattern, this may be due to the large volume of the basin and low K value. The short-term groundwater level fluctuation response lag time to rainstorms ranged between 2 and 7 weeks depending on the specific yield and the depth of the water level. The groundwater flow direction is almost similar to the surface water, and the water table pattern is almost reflecting the surface topography, except someplace disturbed by faults or joints. The effect of transpiration on the groundwater level depends on the depth of the groundwater table and the intensity of evaporation, as evaporation and transpiration in the deep-water layers are very little. It is noted that the fluctuation of the groundwater level in areas where there is little vegetation cover. The flow of running water into the Great Zab in a part of the free aquifer raises the level of the groundwater near the river basin. There is an interrelationship between rivers and the level of water layers, and when the groundwater level rises, it receives water from the groundwater system. Urban growth leads to changes in land cover through vegetation cover and different terrain, the extraction of groundwater, and the increase of impermeable areas. All these factors affect the seepage and recharge of groundwater. These data indicate that raising the groundwater table can be achieved by increasing the green area in the study area. This would lead to an increase in groundwater recharge in addition to avoiding the drilling of new wells and increasing the control of existing wells. Artificial factors: The pumping of water from the aquifers through wells is followed by a drop in the groundwater level around the well. Therefore, the artificial feeding of groundwater, such as the injection of water into the aquifers by injection wells, raises the level of the groundwater. According to the internal report of the Erbil Groundwater Directorate, 2022, currently, there is no artesian well in the central sub-basin of Erbil due to the low levels of the piezometric surface inside the confined aquifer. Precipitation is forming the main recharge, and from the underlying aquifers especially in the north part, this recharging is probably from lower aquifers through leakage through permeable formations, joints, and faults. The main discharge is the withdrawal from wells and outflow from the basin to adjacent aquifers, especially to the Gwer basin.

To make recommendations based on the results of this study and for future research, very deep wells that penetrate the aquifers must be drilled for research and studies. Well loggings and geophysical studies are required to determine the area's more accurate lithology, stratigraphy, and structural geology, especially in high-yielding areas, in order to study the water balance and perennial yield in greater detail. The model is being used to predict and manage groundwater. Using morphometric analysis to locate small dams and ponds, as well as recharging wells, for collecting rainwater in order to develop a conjunctive use and drainage basin management plan to replenish groundwater. The estimation of perennial yield is strongly advised, this could be accomplished by conducting more detailed programmed pumping tests over a longer period of time, in specific locations and at specific times, as well as observing the water tables this is for the best management and maximum perennial yield. Investigate aquifer chemistry according to depth and the layer containing such qualities, this aids in water resource management and utilization. Investigate the conductivity of the basin's boundaries to estimate the rate and amount of inflow and outflow of the basin in order to develop the maximum. Construction of a discharge station at the Erbil city outlet to determine the precise surface runoff. As a result, a portion of the water surplus will be known. Aquifers should be regularly monitored by setting up observation wells in all types of aquifers and constantly monitoring the fluctuations of the groundwater table. The government should control all illegal (or pile) wells to avoid a cluster of wells within the region and the depletion of groundwater level (which may lead to losing characteristics of the aquifer). To improve groundwater system management, the following factors must be considered for a successful management policy; (i) Physical dimensions of the amount of water that can be exploited and the potential for groundwater recharge, (ii) A hydrodynamic equilibrium between natural and/or artificial recharge and groundwater abstraction rates must be maintained, (iii) Chemical dimensions of groundwater quality variations during recharge or exploitation processes, (iv) Degradation in groundwater quality must not be allowed, (v) The natural environment, particularly sensitive aquatic ecosystems, must be protected.

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APPENDICES

Appendix- 1. Relative humidity (%) data of Erbil for the period between 2001 and 2021 (data were collected from Erbil meteorological station)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2001	74.00	50.00	35.00	26.00	23.00	24.00	23.00	35.00	53.00	63.00	65.00	65.00
2002	76.00	61.00	59.00	64.00	36.00	22.00	23.00	26.00	28.00	39.00	51.00	73.00
2003	83.00	71.30	63.80	56.30	35.90	25.20	25.00	25.12	32.20	42.10	57.10	75.10
2004	76.40	72.60	51.60	47.80	39.50	23.80	23.20	25.00	24.50	35.10	72.90	69.70
2005	70.10	68.70	58.80	48.00	38.20	28.10	22.00	26.90	29.30	34.50	53.00	57.40
2006	71.60	68.90	53.30	61.30	42.90	25.80	28.80	26.20	32.40	52.20	61.30	53.80
2007	69.40	75.00	64.30	62.80	43.10	32.40	29.40	32.50	32.50	35.60	46.90	57.70
2008	61.70	63.10	48.40	37.20	31.00	27.60	24.30	26.60	32.00	48.80	58.10	58.80
2009	59.50	56.80	61.30	51.20	31.40	24.70	27.00	27.90	33.10	36.90	61.70	72.50
2010	67.00	66.00	60.20	58.60	40.10	27.00	26.20	24.60	30.70	45.60	45.20	59.30
2011	75.40	73.00	65.50	58.40	45.30	39.10	25.70	27.30	34.10	43.60	55.60	56.00
2012	74.40	63.60	61.70	49.00	41.50	25.80	22.10	28.50	29.00	48.60	64.60	77.20
2013	73.90	75.60	61.60	53.90	47.70	31.20	29.10	28.70	37.80	39.40	67.90	66.00
2014	72.10	56.00	66.20	48.60	39.80	30.30	29.00	28.30	39.80	58.60	65.60	74.70
2015	72.5	68.40	64.30	52.20	34.50	33.20	25.40	30.80	29.90	54.60	69.80	67.70
2016	76.40	65.30	55.20	53.90	40.50	32.00	27.30	30.50	39.40	41.00	47.50	76.40
2017	68.84	63.50	65.52	58.30	38.06	34.97	32.19	31.26	31.30	44.07	62.03	60.10
2018	61.60	71.60	57.20	52.10	50.50	38.00	34.30	31.20	32.00	47.50	73.60	82.10
2019	73.60	71.60	74.40	71.30	45.00	32.80	31.80	31.90	32.90	47.90	52.70	76.10
2020	80.90	78.90	73.80	66.70	55.60	37.00	29.50	35.10	33.00	38.90	66.00	71.10
2021	67.00	76.20	60.10	48.90	39.10	31.90	33.00	29.50	36.50	48.10	57.00	77.90

Appendix- 2. Temperature (ºC) data of Erbil for the period between 2001 and 2021 years (data were collected from Erbil meteorological station)

Year	Temp	Months												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg.
	Min	3.50	5.10	10.30	12.90	16.80	22.60	26.70	26.50	22.50	16.80	8.90	6.80	
2001	Max	14.30	15.30	21.80	25.90	38.80	38.80	42.60	42.50	37.70	30.30	20.00	14.80	
	Avg.	8.90	10.20	16.05	19.40	27.80	30.70	34.65	34.50	30.10	23.55	14.45	10.80	21.76
	Min	3.30	5.10	8.60	12.20	16.60	23.20	27.10	24.70	21.60	18.40	10.30	4.60	
2002	Max	11.50	16.50	20.60	21.50	39.60	39.60	42.00	40.30	37.50	31.40	22.50	11.50	
	Avg.	7.40	10.80	14.60	16.85	28.10	31.40	34.55	32.50	29.55	24.90	16.40	8.05	21.26
	Min	5.10	4.70	6.80	12.90	18.20	23.60	26.10	27.10	21.50	18.30	9.50	4.00	
2003	Max	14.10	12.70	16.30	23.60	33.00	38.70	41.60	42.90	36.30	31.00	20.40	13.50	
	Avg.	9.60	8.70	11.55	18.25	25.60	31.15	33.85	35.00	28.90	24.65	14.95	8.75	20.91
	Min	5.80	4.80	9.20	12.60	18.10	23.10	26.80	25.10	22.50	18.30	10.50	2.70	
2004	Max	13.30	13.90	21.90	23.80	30.80	38.40	42.40	41.00	38.30	32.10	18.70	13.20	
	Avg.	9.55	9.35	15.55	18.200	24.45	30.75	34.60	33.05	30.40	25.20	14.60	7.95	21.14
	Min	4.00	4.20	8.50	14.40	19.00	23.90	28.10	28.40	22.40	17.70	9.40	7.70	
2005	Max	12.60	12.90	18.70	26.30	31.90	38.50	43.30	42.10	36.90	30.20	21.20	19.40	
	Avg.	8.30	8.55	13.60	20.35	25.45	31.20	35.70	35.25	29.65	23.95	15.30	13.55	21.74
	Min	4.20	6.40	10.00	15.50	19.90	25.20	28.10	29.90	23.50	21.70	9.30	3.90	
2006	Max	11.80	14.80	21.60	25.70	33.00	41.40	41.00	43.30	36.80	29.70	19.50	2.00	
	Avg.	8.00	10.60	15.80	20.60	26.45	33.30	34.55	36.60	30.15	25.70	14.40	8.95	22.09
	Min	2.90	5.80	8.30	11.30	22.50	25.20	28.20	27.90	23.70	19.30	10.70	5.30	
2007	Max	11.50	14.20	18.20	21.10	33.20	38.80	41.20	41.00	37.80	31.10	21.40	15.50	
	Avg.	7.20	10.00	13.25	16.20	27.85	32.00	34.70	34.45	30.75	25.20	16.05	10.40	21.50
	Min	1.30	5.40	12.80	17.50	19.00	25.00	27.80	29.20	24.90	18.10	11.80	5.30	
2008	Max	10.60	13.90	24.20	28.8	31.2	38.3	41.50	42.00	36.30	27.9	20.6	15.00	
	Avg.	5.95	9.65	18.50	23.15	25.10	31.65	34.65	35.60	30.60	23.00	16.20	10.15	22.02
	Min	3.40	9.60	9.60	13.00	20.50	26.50	27.60	26.30	22.10	18.49	11.60	15.3	
2009	Max	130	16.10	17.40	23.30	31.90	37.90	39.90	39.50	33.30	30.21	19.92	9.10	
	Avg.	8.20	12.85	13.50	18.15	26.20	32.20	33.75	32.90	27.70	24.35	15.76	12.20	21.48
	Min	8.70	8.77	12.30	14.30	20.40	26.10	28.50	29.90	25.30	19.45	13.01	8.20	
2010	Max	15.02	15.90	20.50	24.30	31.40	38.90	42.20	42.40	38.20	30.10	25.53	18.40	
	Avg.	11.86	12.34	16.40	19.30	25.90	32.50	35.35	36.15	31.75	24.78	19.27	13.30	23.24
	Min	5.40	6.30	9.00	14.90	19.80	25.70	29.00	28.20	23.60	17.30	8.10	5.50	
2011	Max	12.40	13.80	18.90	23.90	30.30	37.70	41.90	40.70	35.70	27.40	17.00	16.00	
	Avg.	8.90	10.05	13.95	19.40	25.05	31.70	35.45	34.45	29.65	22.35	12.55	10.75	21.19
	Min	4.60	5.60	6.90	16.90	21.70	27.20	30.00	28.80	24.40	19.10	13.30	7.10	
2012	Max	11.80	13.50	15.50	27.00	32.50	39.10	41.80	41.50	37.20	29.80	21.00	4.90	
	Avg.	8.20	9.55	11.20	21.95	27.10	33.15	35.90	35.15	30.80	24.45	17.15	6.00	21.72
	Min	2.20	7.70	10.00	14.50	19.40	24.80	27.30	27.10	22.00	17.50	12.80	5.60	
2013	Max	12.70	16.40	19.90	26.20	31.20	38.00	41.30	41.00	35.60	28.90	21.90	13.60	
	Avg.	7.45	12.05	14.95	20.35	25.30	31.40	34.30	34.05	28.80	23.20	17.40	9.60	21.57
	Min	6.10	6.20	11.00	14.50	20.80	25.10	28.20	27.90	23.10	17.70	9.70	7.60	
2014	Max	15.00	16.80	20.70	26.70	33.70	38.50	41.80	42.70	36.00	27.90	19.50	15.90	
	Avg.	10.60	11.50	15.80	20.60	27.30	31.80	35.00	35.30	29.60	22.80	14.60	11.70	22.22
	Min	4.50	6.00	8.70	13.40	21.20	25.00	28.90	28.30	25.90	19.60	10.30	5.60	
2015	Max	13.60	16.00	19.70	25.00	33.60	38.00	43.40	42.60	38.60	29.60	19.80	14.20	
	Avg.	9.05	11.00	14.20	19.20	27.40	31.50	36.15	35.45	32.25	24.60	15.05	9.90	22.15
	Min	4.10	7.30	10.00	14.50	19.90	26.90	28.60	28.90	23.00	18.00	9.10	4.60	
2016	Max	11.70	17.00	25.20	24.80	32.30	38.20	42.30	43.40	36.00	31.00	22.00	12.70	
	Avg.	7.90	12.15	17.60	19.65	26.10	32.55	35.45	36.15	29.50	24.50	15.55	8.65	22.15
	Min	3.26	3.44	9.78	13.59	20.33	24.63	29.58	28.93	25.19	17.84	11.90	8.90	
2017	Max	20.12	18.32	24.67	42.98	38.78	43.80	43.59	39.84	29.43	29.43	21.70	18.70	
	Avg.	11.69	10.88	17.22	28.29	29.56	34.21	36.58	34.38	27.31	23.64	16.80	13.80	23.70
	Min	6.60	8.10	13.50	15.70	20.60	25.70	28.90	27.60	25.40	20.90	12.20	8.60	
2018	Max	14.70	16.70	23.20	26.70	31.00	37.90	42.00	41.50	38.30	30.50	19.70	14.40	
	Avg.	10.65	12.40	18.35	21.20	25.80	31.80	35.45	34.55	31.85	25.70	15.95	11.50	22.93

2019	Min	6.00	6.70	8.50	10.96	19.80	25.70	25.40	29.50	23.50	19.90	11.00	8.50	
	Max	13.00	14.90	16.30	20.47	32.60	40.30	40.80	40.20	36.80	30.90	22.20	16.00	
	Avg.	9.50	10.80	12.40	15.72	26.20	33.00	33.10	34.85	30.15	25.40	16.60	12.25	21.66
2020	Min	5.60	6.50	19.40	13.40	19.50	30.70	30.00	27.30	26.10	19.20	13.30	7.10	
	Max	12.50	13.20	11.60	24.00	32.30	37.70	42.70	39.40	39.30	32.40	20.90	16.40	
	Avg.	9.05	9.85	15.50	18.70	25.90	34.20	36.35	33.35	32.70	25.80	17.10	11.75	22.52
2021	Min	6.20	7.30	9.70	15.60	22.50	24.00	28.70	28.40	21.80	17.90	12.20	7.20	
	Max	15.40	17.10	19.50	29.10	35.60	39.60	42.70	41.80	36.10	29.90	22.80	15.60	
	Avg.	10.80	12.20	14.60	22.35	29.05	31.80	35.70	35.10	28.95	23.90	17.50	11.40	22.78

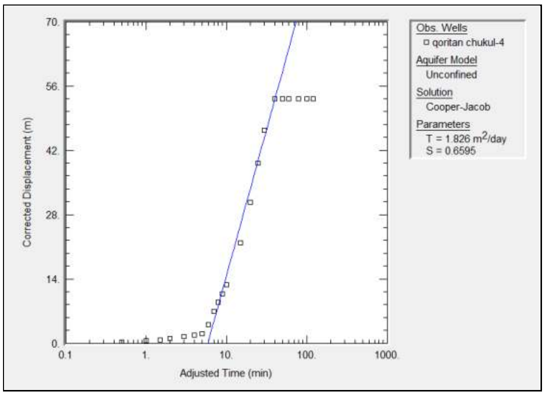
Appendix- 3. Sun shine data of Erbil for the period between 2001 and 2021 years (data were collected from Erbil meteorological station)

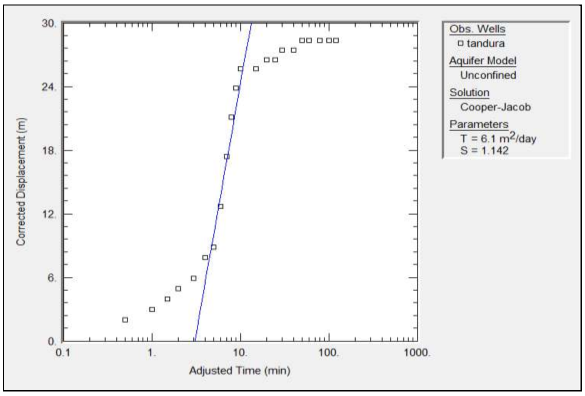
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2001	3.60	5.90	8.60	9.77	11.50	11.00	12.30	9.40	7.40	7.60	4.80	5.50
2002	4.80	7.10	6.20	6.42	10.70	12.10	11.80	11.60	10.50	6.40	6.60	4.00
2003	5.70	4.50	6.00	6.7	10.20	11.50	11.40	11.30	10.40	7.40	5.70	4.00
2004	3.70	4.90	7.40	7.90	9.42	12.00	12.00	10.70	10.50	7.70	4.90	5.30
2005	4.40	5.60	7.00	7.60	8.20	11.30	11.70	10.80	10.20	7.50	6.50	5.80
2006	3.80	4.10	7.70	6.60	8.90	11.80	11.20	10.10	10.50	6.70	7.50	6.10
2007	5.40	5.10	6.90	5.90	6.80	11.30	11.10	11.00	10.20	7.60	6.70	6.20
2008	5.70	5.50	7.10	8.00	9.60	10.80	10.50	10.00	7.30	7.00	6.80	6.00
2009	6.60	4.30	4.80	8.00	8.80	9.10	9.90	10.70	9.10	7.90	6.10	3.30
2010	3.50	4.10	3.70	6.70	8.10	10.00	11.40	10.60	9.50	7.40	8.80	5.80
2011	4.90	5.20	7.80	4.50	6.00	9.80	9.90	10.80	10.50	8.20	6.50	6.50
2012	4.80	5.90	6.20	8.50	9.20	12.00	11.50	11.50	9.70	7.50	5.40	5.30
2013	4.50	6.10	6.30	8.80	8.80	12.60	12.50	12.00	10.80	9.80	6.60	5.50
2014	5.50	8.80	7.10	7.70	9.90	12.00	12.70	12.00	11.30	7.30	6.50	4.90
2015	5.60	5.90	7.40	8.40	8.70	11.10	12.30	11.70	9.70	6.70	6.60	6.40
2016	4.70	6.50	7.20	9.50	9.50	10.30	12.40	11.22	10.90	9.10	7.80	4.90
2017	6.48	7.47	5.51	8.51	11.10	14.30	13.40	12.90	11.20	8.74	6.35	6.30
2018	5.30	4.80	6.90	8.20	9.40	13.70	13.40	12.00	11.50	5.90	4.50	3.50
2019	4.90	5.70	5.00	7.40	11.40	12.90	13.90	11.90	10.90	8.20	8.30	4.90
2020	4.30	5.10	6.40	5.10	10.60	12.60	11.70	12.20	11.20	10.20	5.10	6.50
2021	4.30	7.60	7.20	8.70	11.00	13.00	12.50	11.50	11.00	8.50	7.10	5.10

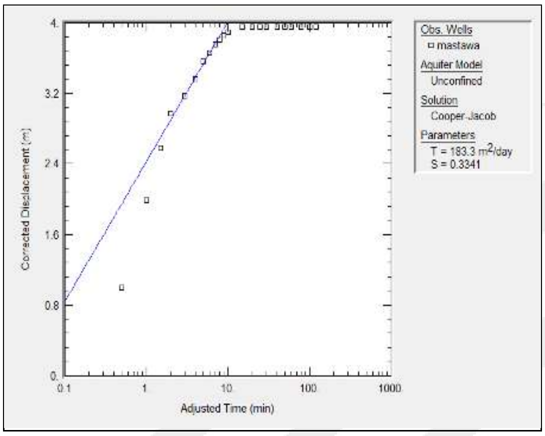
Appendix- 4. Monthly average of evaporation (mm) data of Erbil for the period between 2001 and 2021 years (data were collected from Erbil meteorological station).

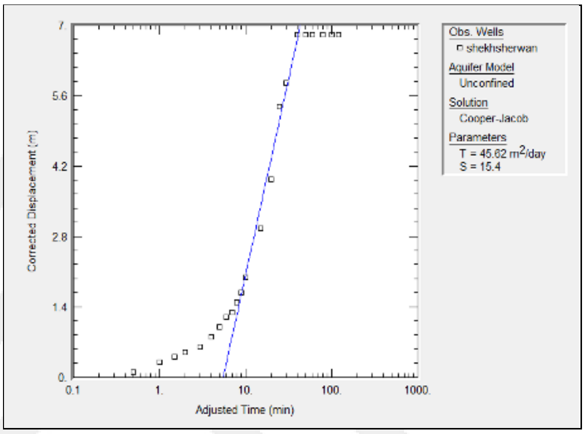
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	sum.
2001	1.8	2.00	3.40	4.70	7.90	10.30	10.60	10.90	8.48	5.00	2.80	1.13	68.99
2002	1.10	2.55	4.10	4.10	8.20	10.30	13.60	13.30	8.50	5.50	3.20	1.30	75.75
2003	1.70	1.80	3.40	5.00	9.40	12.90	13.60	13.80	10.00	6.40	3.00	1.40	82.40
2004	1.40	1.70	4.60	6.40	9.40	13.60	14.30	12.90	10.50	6.80	2.30	1.20	85.10
2005	1.40	2.10	3.80	6.20	9.10	12.40	13.20	12.10	9.30	6.40	2.60	2.30	80.9
2006	1.40	1.90	4.40	5.20	9.20	12.90	13.50	12.30	9.00	5.60	2.30	2.06	79.76
2007	1.80	2.40	4.10	5.10	10.4	14.10	15.90	14.10	11.40	8.40	4.30	2.60	94.60
2008	2.00	2.90	6.50	10.20	11.70	14.90	16.00	15.40	11.10	6.50	3.90	2.60	103.70
2009	2.30	3.60	4.30	6.40	10.30	14.00	13.00	12.40	9.30	6.90	3.30	1.80	87.60
2010	2.80	2.80	4.90	5.20	9.80	13.30	13.90	9.60	9.60	6.20	4.70	2.60	85.40
2011	1.60	2.30	4.3	6.30	8.60	12.80	12.80	11.70	8.70	5.50	2.60	2.50	79.70
2012	1.70	2.90	3.60	6.90	10.00	13.30	13.60	12.30	9.20	5.40	2.80	1.70	83.40
2013	1.50	2.20	4.00	5.00	7.20	10.50	11.30	10.50	8.10	6.50	2.60	1.70	71.10
2014	1.50	3.10	3.60	5.50	8.8	11.80	12.80	11.70	8.80	4.40	2.40	1.40	75.80
2015	1.50	2.00	3.10	4.90	9.50	12.00	12.10	11.60	9.00	5.00	2.60	1.60	74.90
2016	1.30	2.40	3.90	6.50	8.30	11.90	12.40	12.89	8.40	5.70	3.50	1.30	65.60
2017	1.70	2.60	3.00	4.60	9.00	11.00	13.20	13.50	10.10	6.80	2.90	2.60	81.00
2018	2.20	2.20	4.80	6.90	7.90	11.40	12.90	11.20	9.50	6.00	2.20	0.90	78.10
2019	1.60	1.80	2.20	4.30	10.30	14.70	14.00	18.50	11.60	9.70	4.80	2.20	95.70
2020	1.80	4.30	4.70	4.30	9.90	14.30	16.30	14.60	12.80	7.80	3.60	2.30	96.70
2021	1.80	2.70	3.80	7.80	12.60	15.60	17.20	15.60	11.30	8.00	4.10	2.30	102.8

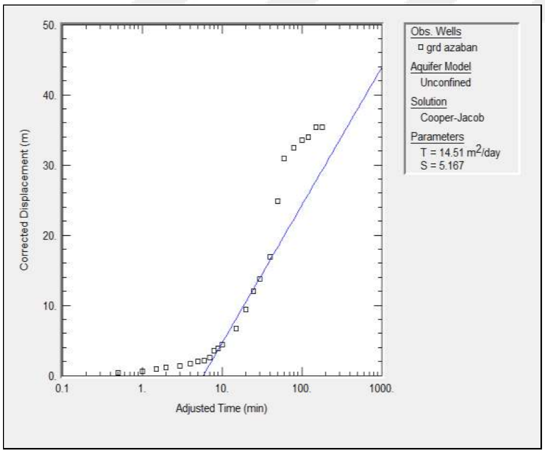
Appendix- 5. Jacob straight line (1948) plots for 23 wells created by AQTESOLV program.

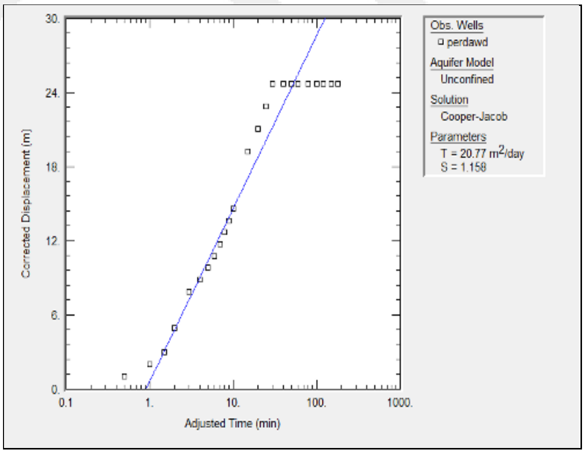


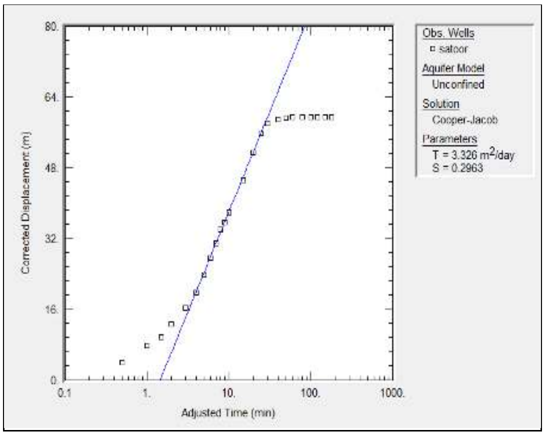


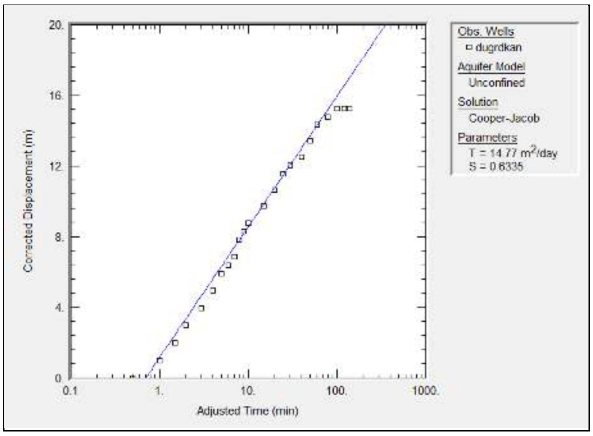


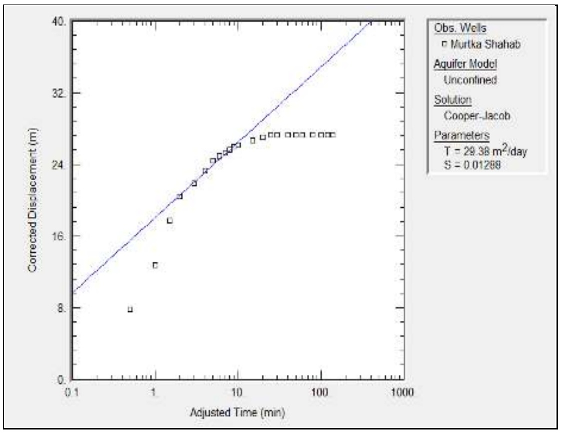


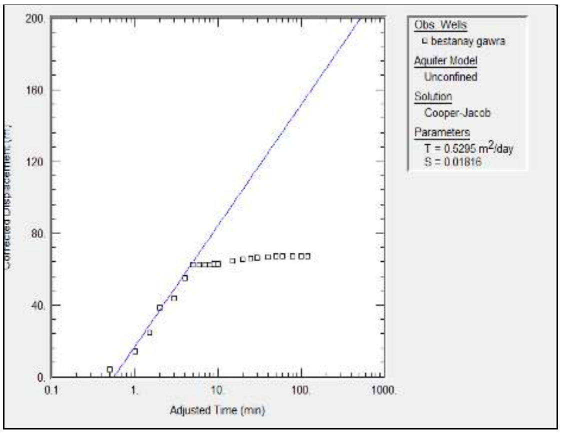


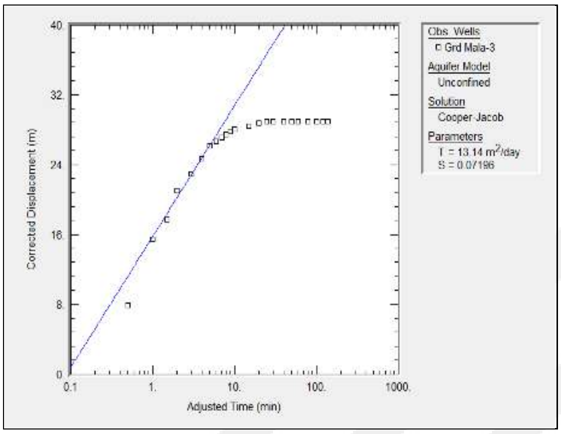


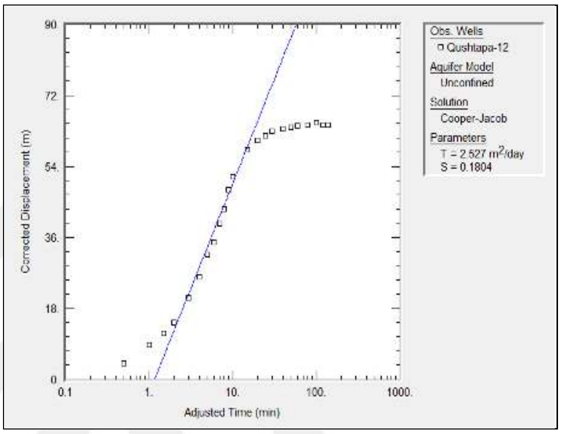


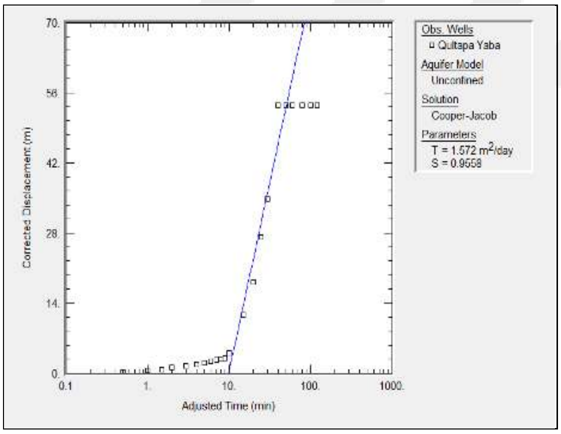


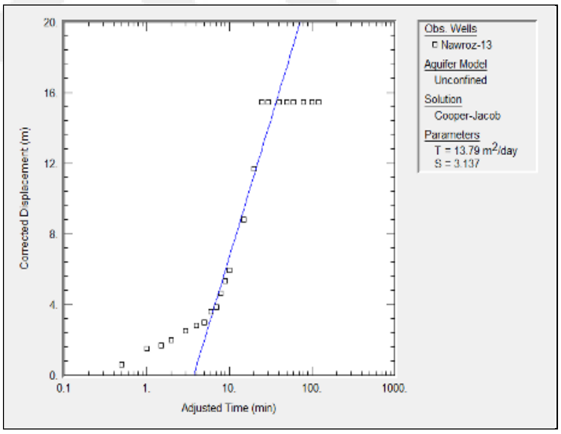

Corrected Displacement (m)
Adjusted Time (min)
Obs. Wells
Murtka Shahab
Aquifer Model
Unconfined
Solution
Cooper-Jacob
Parameters
T = 29.38 m2/day
S = 0.01288

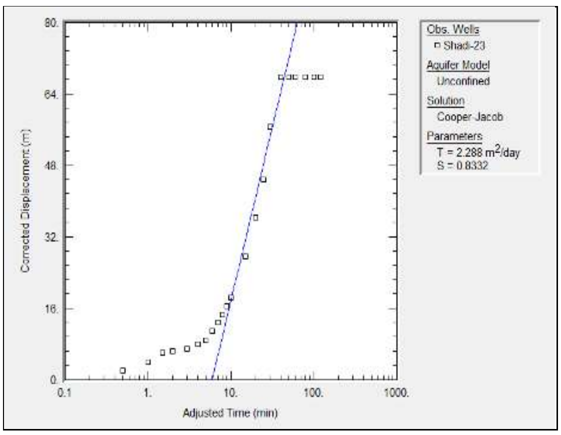

Adjusted Time (min)
Obs. Wells
bestanay gawra
Aquifer Model
Unconfined
Solution
Cooper-Jacob
Parameters
T = 0.5295 m2/day
S = 0.01816

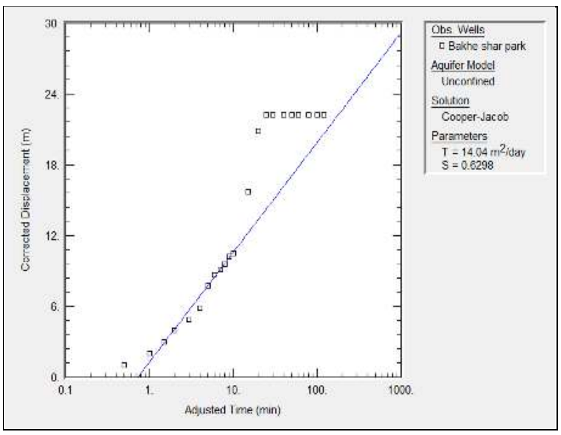

Corrected Displacement (m)
Adjusted Time (min)
Obs. Wells
Grd Mala-3
Aquifer Model
Unconfined
Solution
Cooper-Jacob
Parameters
T = 13.14 m2/day
S = 0.07196

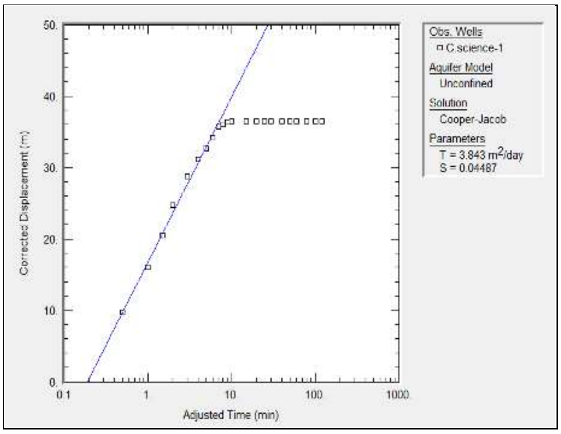

Corrected Displacement (m)
Adjusted Time (min)
Obs. Wells
Qushtapa-12
Aquifer Model
Unconfined
Solution
Cooper-Jacob
Parameters
T = 2.527 m2/day
S = 0.1804


Corrected Displacement (m)
Adjusted Time (min)
Obs. Wells
Qultapa Yaba
Aquifer Model
Unconfined
Solution
Cooper-Jacob
Parameters
T = 1.572 m2/day
S = 0.9558

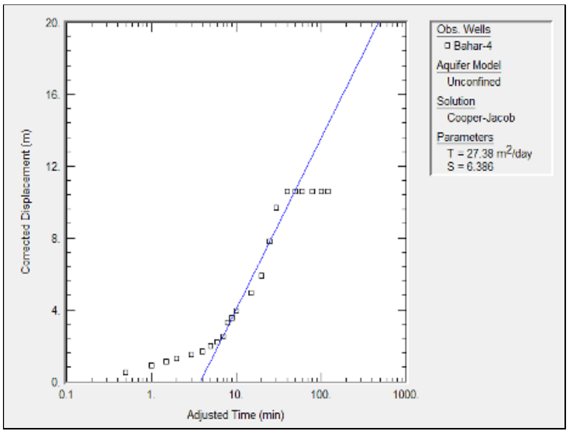

Corrected Displacement (m)
Adjusted Time (min)
Obs. Wells
Nawroz-13
Aquifer Model
Unconfined
Solution
Cooper-Jacob
Parameters
T = 13.79 m2/day
S = 3.137


Corrected Displacement (m)
Adjusted Time (min)
Obs. Wells
Shadi-23
Aquifer Model
Unconfined
Solution
Cooper-Jacob
Parameters
T = 2.288 m2/day
S = 0.8332

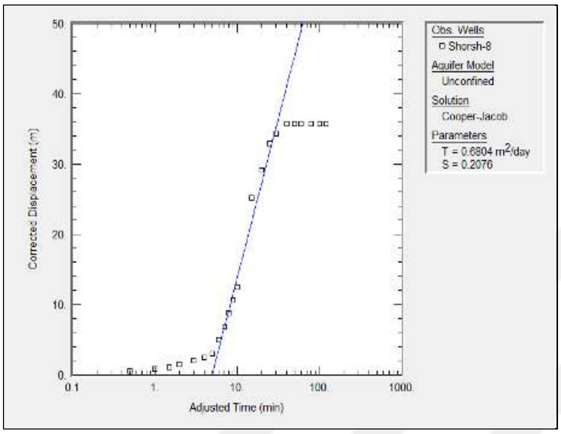

Corrected Displacement (m)
Adjusted Time (min)
Obs. Wells
Bakhe shar park
Aquifer Model
Unconfined
Solution
Cooper-Jacob
Parameters
T = 14.04 m2/day
S = 0.6298



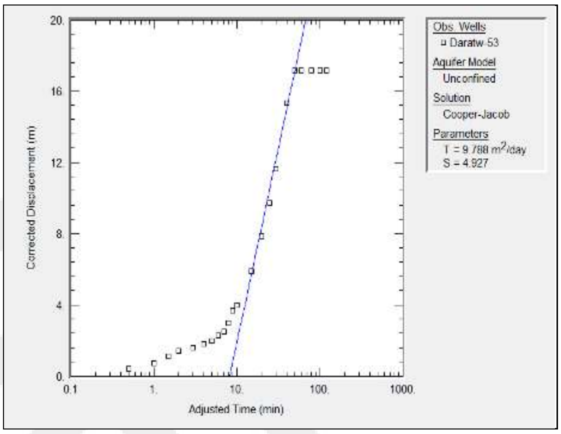
Obs. Wells
C science-1
Aquifer Model
Unconfined
Solution
Cooper-Jacob
Parameters
T = 3.843 m^2/day
S = 0.04487
Corrected Displacement (m)
Adjusted Time (min)



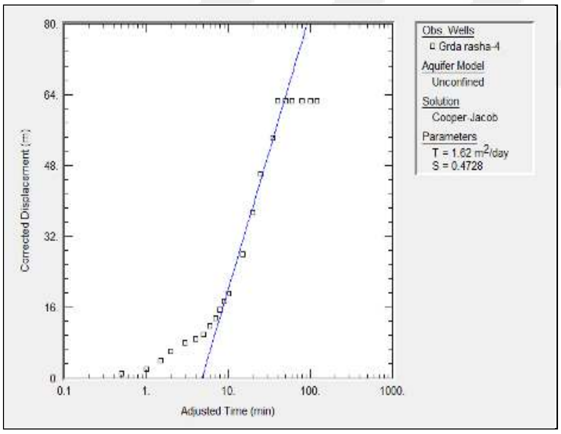
Obs. Wells
Bahar-4
Aquifer Model
Unconfined
Solution
Cooper-Jacob
Parameters
T = 27.38 m^2/day
S = 6.386
Corrected Displacement (m)
Adjusted Time (min)



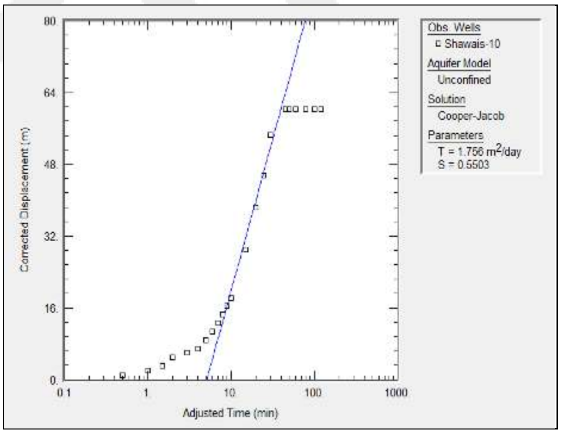
Obs. Wells
Shorsh-8
Aquifer Model
Unconfined
Solution
Cooper-Jacob
Parameters
T = 0.6804 m^2/day
S = 0.2076
Corrected Displacement (m)
Adjusted Time (min)



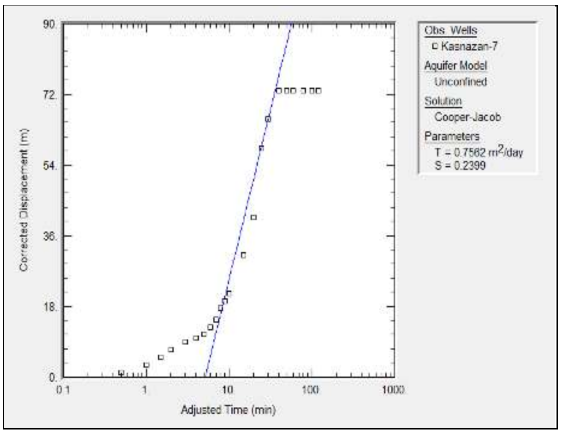
Obs. Wells
Daratw-53
Aquifer Model
Unconfined
Solution
Cooper-Jacob
Parameters
T = 9.788 m^2/day
S = 4.927
Corrected Displacement (m)
Adjusted Time (min)



Obs. Wells
Grda rasha-4
Aquifer Model
Unconfined
Solution
Cooper-Jacob
Parameters
T = 1.62 m^2/day
S = 0.4728
Corrected Displacement (m)
Adjusted Time (min)



Obs. Wells
Shawais-10
Aquifer Model
Unconfined
Solution
Cooper-Jacob
Parameters
T = 1.756 m^2/day
S = 0.5503
Corrected Displacement (m)
Adjusted Time (min)



Obs. Wells
Kasnazan-7
Aquifer Model
Unconfined
Solution
Cooper-Jacob
Parameters
T = 0.7562 m^2/day
S = 0.2399
Corrected Displacement (m)
Adjusted Time (min)

CURRICULUM VITAE

Nashwan Jalal Smail KHOSHNAW

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