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# Hydrological study and assessment of water budget for Erbil basin, Kurdistan region, Iraq

**Jwan Sabah Mustafa[1]* and Dana Khider Mawlood[1,2]**
[1]Department of Civil Engineering, College of Engineering, Salahaddin University, Erbil, Iraq
[2]Vice president in University of Kurdistan-Hawler (UKH), Erbil, Iraq
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*to whom all correspondence should be addressed: e-mail: juan.sabah@yahoo.com
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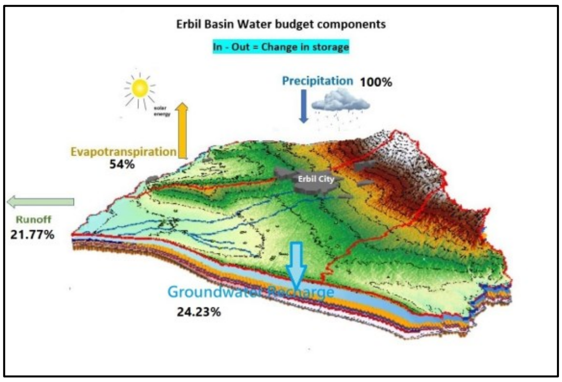
## Graphical abstract



## Abstract

This research is conducted on Erbil basin, it is located in northern part of Iraq, the basin is composed of three main sub-basins which are: Northern part (Kapran), Central sub-basin and Southern part (Bashtepa) respectively. The total area of three sub-basins is approximately (3,200 km$^2$). The main sources of aquifer recharge in the study area is depends on precipitation. The article estimated the percentage and amount of water budget elements for the selected basin. Therefore, the paper evaluates the obtained climate data form Erbil meteorological station for (25 years) to evaluate the water budget in the study area. The main objective to assess the Erbil basin water budget and determine amount of the each parameters related to the study area. Based on the results of this study data analysis the amount of the mean monthly temperature (18.94 Č), and sun shine (8.18 hr/day), the average relative humidity is (47.82%), the evaporation percentage is (54%) of the precipitation. The study concluded that the amonut of the rainfall data is (394.65mm) and the percentage of precipitation over Erbil basin is (100%), the Recharge into groundwater is (24.23%), the Runoff and Evporation are (21.77%) and (54%) respectively. The study employed the MODFLOW-2000 package within the Groundwater Modeling System (GMS), a computer program utilizing a finite difference numerical method to solve three-dimensional groundwater flow equations. Conducted on the Erbil plain, the research aimed to develop an acceptable and calibrated model, shedding light on the hydraulic properties of the aquifer systems in the region. Calibration was achieved by comparing observed field values with simulated heads, resulting in a good coefficient of determination. The findings highlight the significance of groundwater modeling as a powerful tool for managing and planning aquifer systems in any selected region. By providing a detailed understanding of the groundwater dynamics in the Erbil basin, this study contributes to the sustainable use of water resources and facilitates informed decision-making for future development and conservation efforts. The research underscores the broader applicability of groundwater modeling in addressing water management challenges and emphasizes its role in supporting environmentally sound practices for the benefit of communities and ecosystems.

**Keywords**: Hydrological study, Evaporation, Recharge, Runoff, Rainfall, Water balance, GMS.

## 1. Introduction

The study area was characterized as being located in an arid or semi-arid region, therefore, it was deemed essential that water demand in the region be provided by management. The area was determined to have high values of the evaporation rate and water recharge to the ground. Meanwhile, the area was also characterized as having high velocity with low duration that could lead to flooding (Fathy *et al*. 2021). The study area was mainly depended on by rainfall to recharge the aquifers in the area. Since, water demand was increased with the increasing population growth. The climate and hydrogeological condition of any area were reflected by the nature of the area which directly impacted the hydrological cycle. The principle of the water balance equation was applied as the application of the mass conservation law, and was mainly referred to as the continuity equation. That, said the difference between all the input and output for any control volume and period were balanced by the change in storage. In this study, the water balance application was used to predict the consequences of artificial changes in the groundwater

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basins (Al sudani 2019). Erbil basin was divided into three main sub-basins that were: (Kapran, Central, and Bashtepa) also called as (Northern, central and Southern) respectively. The rock of the study area consisted of the (Upper Miocene – Recent) and which was mainly consisted; Muqdadiya, Bai Hassan formations and also Quaternary deposits (Hassan 1998). While, several previous studies had calculated water balance for particular locations, from these studies that were conducted in Erbil area are; the Hydrogeological Study of Central sub-basin (Hassan 1981), also the study of water balance of central part of Erbil basin by (Al-kubaisi *et al* 2019). The study of water balance for Khanaqin basin, east of Iraq by (Al-Sudani 2018). Then the study on groundwater recharge was conducted using meteorological water balance in khan area (Al-Sudani 2018). As well as, another study on Erbil basin groundwater recharge potential zone was used using fuzzy-Analytical Hierarchy Process (AHP) in the north part of Iraq (Hamad 2022). A study was being conducted on the impact of climate change on the water balance of Erbil basin. Erbil basin was being faced with threats from rising temperatures and shifting rainfall patterns due to global warming. To understand how these climate shifts could affect the basin's hydrology, the water balance under current and projected future climate scenarios was being modeled. Meteorological data such as precipitation, temperature, humidity and wind speed over the past few decades had been collected and analyzed. (Nanakaley 2019). A water balance was calculated for the period 2006-2021, using meteorological data from Erbil station. Potential evapotranspiration was estimated at 1564.mm using the Thornthwaite technique. The water surplus was determined to be 64.3 mm, and the water deficit was estimated to be 1,848.7 mm. Annual surface runoff and recharge were determined to be, respectively, 46.97 mm and 31.46 mm. The climate of the Erbil basin was concluded to be arid based on the results of the water balance calculation. (Jalal 2022). A study was conducted by (Hassan 2022) on groundwater modeling in the Kapran sub-basin under transient state flowconditions. MODFLOW was used to predict groundwater conditions in 2039. The aquifer was modeled in an unconfined environment and is represented by a single layer with thicknessesranging from 280m to 640m. The groundwater data for period (2003-2021) was used for calibration of the model, the results of the model fits very well with the observed data, then the model was run to predict the groundwater condition for the next 18 years (2021-2039). The result predicts 42m (2.33 m/year) ground water drawdown for the prediction period. As well as, in the same study presents that the excessive exploitation of groundwater in the Northern Erbil basin resulted in a (49.74m) drawdown across the study region from (2003 to 2021), equivalent to (2.76 m/year) decline in groundwater, due to thousands of illegall wells drilled in the study area. In general, large amounts of water were used without a defined policy for the use of water resources and water sustainability. The lack of understanding among individuals and institutions was found to have a substantial influence on groundwater depletion. The Erbil aquifer will be depleted due to continuing negligence and recklessness in the usage of water resources. Then the study of (Rafaat 2023) was conducted who studied on Bastora catchment area that was located in the northern part of Erbil basin, which has a semi-arid to arid climate condition, with cold and rainy winters and hot and dry summers. Based on the Soil Conversation Service (SCS) method, the surface runoff was determined to reach (195 mm/year) and the groundwater budget was calculated to be (24.5 $m^3$ /year). The soil type was classified as (type B) and the curve number was determined to be (CN=72) according to the results of hydrological modelling. Based on the Horton model equation and double ring methods, the infiltration rate was estimated to be 195.75 and 18.25 mm/hr respectively. Rainfall is the only input element in the water balance, this element affects surface runoff and groundwater recharge, representing the outputs of the water balance elements. The study was limited due to the accuracy of the meteorological data, and monthly data was only obtained for periods of (1995-2020), while more data could have provided a better estimation and prediction for future aspects. Thus, due to the fact of increasing inhabitants during the last decades, and due to the establishment of agricultural and industrial projects, groundwater utilization has become a vital resource and alternative to surface water in the study area region.

The main objective of this study was to determine the water budget of the Erbil groundwater basin, which is very important for managing and keeping sustainability of water resources in the region.

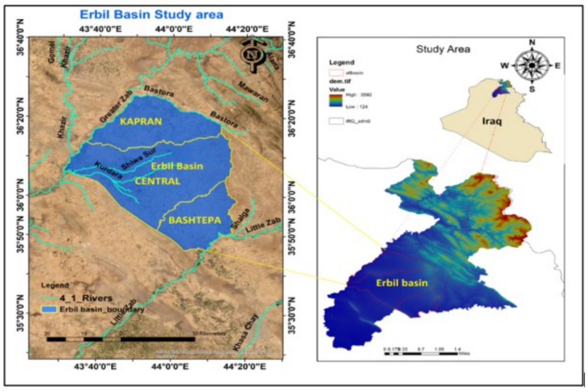

**Figure 1.** Location of the study area, Erbil basin (Arc Map 10.8)

## 2. Materials and methods

### 2.1. Locations of the study area

Erbil basin lies between latitudes (36$^o$ 08' 30" and 36$^o$ 14' 15" ) and Longitudes (43$^o$ 57' 30" and 44$^o$ 03' 20"), The basin is naturally bordered by two rivers of Greater Zab and Lesser Zab forming north and south respectively. From east and north-east, Pirman Dag was acting as a water divide and the Kirkuk structure (Avana and Khurmala domes) restricted the area of study from west and south-west representing the second water divide. The total area of the regional Erbil basin was about (3,200 Km$^2$) which was divided into three main parts according to groundwater flow. The first part was the Kapran basin which was the northern part of Erbil basin, the second was the central part basin which was the intermediate basin, and the third was Bashtepa which lay in the southern part of the Erbil basin (Hassan 1981), see Figure1

### *2.2. Hydrological conditions of the Study area*

The climate data of the Erbil meteorological station had been collected for the period (1995-2020) for this study. The sum and average amount of each parameters were tabulated in Table 1.

**Table 1.** The climate data record in Erbil station for the period (1995-2020)

| **Erbil station data during (1995-2020)** | | | | | | |
|---|---|---|---|---|---|---|
| **Month** | **Winspeed m/s** | **Sunshine hr/day** | **Rainfall mm** | **Relative Humidity%** | **Evaporation (mm)** | **Avg Temp C̊** |
| Oct | 1.92 | 7.86 | 18.61 | 42.18 | 194.18 | 21.09 |
| Nov | 1.71 | 6.50 | 36.92 | 57.72 | 94.73 | 13.50 |
| Dec | 1.83 | 5.19 | 67.63 | 67.70 | 56.22 | 8.47 |
| Jan | 1.97 | 4.91 | 74.27 | 72.39 | 50.70 | 6.95 |
| Feb | 2.20 | 5.81 | 63.13 | 67.23 | 68.45 | 8.20 |
| Mar | 2.37 | 6.57 | 70.88 | 60.69 | 120.09 | 11.97 |
| Apr | 2.36 | 7.49 | 45.68 | 54.30 | 162.71 | 16.78 |
| May | 2.36 | 9.31 | 13.27 | 38.90 | 280.16 | 22.76 |
| Jun | 2.23 | 11.52 | 1.62 | 27.59 | 371.26 | 28.53 |
| Jul | 2.08 | 11.66 | 0.20 | 25.71 | 419.11 | 31.57 |
| Aug | 1.84 | 11.21 | 0.04 | 27.62 | 297.82 | 31.02 |
| Sep | 1.71 | 10.12 | 2.41 | 31.75 | 292.10 | 26.40 |
| Sum | 24.60 | 98.15 | 394.65 | 573.79 | 2407.53 | 227.24 |
| Avg. | 2.05 | 8.18 | 32.89 | 47.82 | 200.63 | 18.94 |

The chart of the climate data are shown in Figure 2

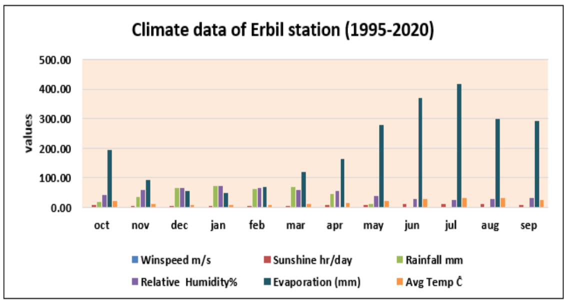

**Figure 2.** The climate data for the periods (1995-2020)

### *2.3. Hydrogeological conditions of the Study area*

According to (Al Kubaisi 2008) who indicated that the intervals of the trend of the center of the depositional basin through Erbil basin had a thickness of about 3048 m. Also, the sediment was composed of the (siltstone, sandstone, and conglomerate) this occurred during the upper Miocene, Pliocene and Pleistocene, an uplift with intensive folding and thrusting and concurrent subsidence of deep basins had occurred in North and North East of Iraq, see Figure 3

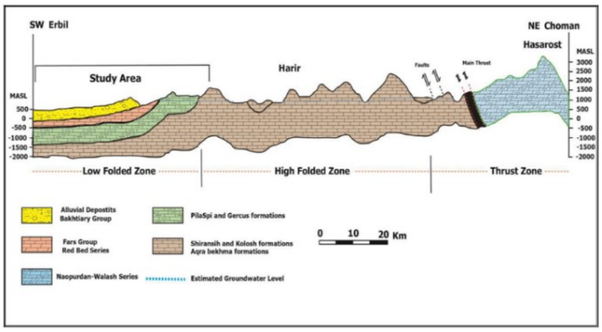

**Figure 3.** Regional hydrogeological cross section of Choman-Erbil (Dizayee 2014)

## 3. Methodology and data analysis

### *3.1. Water budget component calculations*

The meteorological data obtained from Erbil station were analyzed to estimate the water budget and characteristics of the selected region. In order to understand the hydrological conditions of the area. The analysis began by calculating the average annual precipitation and converting the rainfall data into a volume for the periods of (1995-2020), which gave the volume of precipitation over the basin. Obtaining knowledge of the volume of precipitation over the basin was important. In fact, for the Erbil Basin, the precipitation was the most crucial factor because it was the main source of the basin recharge (Dizayee 2014). However, the total amount of precipitation would not infiltrate into the subsurface, some of the precipitation evaporated. The rest of the precipitation ran off the surface. The calculations started by calculating the volume of precipitation over the basin. The water budget equation was:

$$\text{Inflow} - \text{Outflow} = \pm\,\text{change in storage} \tag{1}$$

Precipitation- (Evaporation + Recharge + Runoff) = ± change in storage

### *3.1.1. Precipitation*

$$\text{Volume of precipitation over the basin}\left(\text{m}^3/\text{year}\right) = \text{average annual precipitation}\left(\text{m}/\text{year}\right) \times \text{basin area}\left(\text{m}^2\right) \tag{2}$$

Volume of precipitation over the basin ($m^3$/year) = (0.39465 m/year) × basin area (3,200,000,000 $m^2$) (The value of 0.39465 m/year estimated during the study for periods1995-2020 which is from meteorological data)

Volume of precipitation over the basin ($m^3$/year) = 1,262,880,000 $m^3$ /year

### *3.1.2. Evaporation*

Evaporation was one of an important element to estimate the water balance. However, evaporation was is a variable element and depends on many factors, for instance temperature and humidity. According to the climatic conditions in the study area, the best method to estimate evaporation was called Ivanoff equation such as described in (Hassan ,1998):

$$E = 0.0018\left(t+25\right)^2\left(100-a\right) \qquad (3)$$

Where:

E= monthly probable evaporation (mm)

t= mean monthly temperature (C°)

a= mean monthly relative humidity

Thus, the Ivanoff equation was used to calculate the average annual evaporation rates for each year based on the average annual temperature and precipitation which were calculated from the available climate data from Erbil meteorological station, Table 2

**Table 2.** Evaporation calculation by Ivanof equation

| Month | t | a | 0.0018(t+25)$^2$ | 100 – a | Evaporation (mm) | P(mm) |
|---|---|---|---|---|---|---|
| Oct | 21.09 | 42.18 | 3.8 | 57.8 | 221.1 | 18.61 |
| Nov | 13.50 | 57.72 | 2.7 | 42.3 | 112.8 | 36.92 |
| Dec | 8.47 | 67.70 | 2.0 | 32.3 | 65.1 | 67.63 |
| Jan | 6.95 | 72.39 | 1.8 | 27.6 | 50.8 | 74.27 |
| Feb | 8.20 | 67.23 | 2.0 | 32.8 | 65.0 | 63.13 |
| Mar | 11.97 | 60.69 | 2.5 | 39.3 | 96.7 | 70.88 |
| Apr | 16.78 | 54.30 | 3.1 | 45.7 | 143.5 | 45.68 |
| May | 22.76 | 38.90 | 4.1 | 61.1 | 250.9 | 13.27 |
| Jun | 28.53 | 27.59 | 5.2 | 72.4 | 373.5 | 1.62 |
| Jul | 31.57 | 25.71 | 5.8 | 74.3 | 427.9 | 0.20 |
| Aug | 31.02 | 27.62 | 5.6 | 72.4 | 408.9 | 0.04 |
| Sep | 26.40 | 31.75 | 4.8 | 68.2 | 324.6 | 2.41 |
| sum | | | | | 2540.7 | 394.65 |
| Avg. | | | | | 211.7 | |
| | | | | Evaporation | 54% | |

The volume of evaporation over the basin is calculated by:

$$\text{Volume of Evaporation over the basin }\left(m^3/\text{year}\right) = \text{average annual evaporation }\left(m/\text{year}\right) \times \text{basin area }\left(m^2\right) \qquad (3)$$

The results of the calculations show that the average volume of evaporation over the basin is (681, 955, 200) $m^3$/year, which is (54%) of the total precipitation.

### *3.1.3. Recharge*

The calculation of the evaporation was not involved in the whole calculations for estimating the water balance because a constant rate of 24.23% of precipitation infiltrated into the subsurface. The main source of recharge in the Erbil Basin was precipitation. The recharge rate to unconfined aquifers from precipitation was 24.23% (Hassan 1998). Thus, from infiltration (groundwater recharge) and evaporation rates the Run off in Erbil Basin could be calculated as follows:

$$\text{Average Runoff} = \text{Average annual precipitation}(100\%) - \text{Infiltration rate }\left(24.23\,\%\right) - \text{Evaporation rate}(55\%) \qquad (4)$$

Average Runoff =100 % – 24.23% – 54%

Average Runoff =21.77 %

This calculation shows that 21.77% is surface Runoff. therefore, the total amount of precipitation 54% evaporates, 24.23% infiltrates into the groundwater to be recharge. To show the relation between Temperature and evaporations see Figure 4

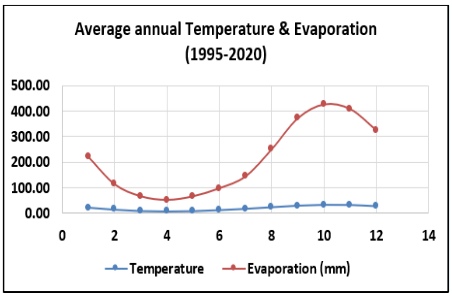

**Figure 4.** The Relation between average annual temperature and average annual evaporation in the study area

To calculate the sustainabe of water use (pumping) in the Erbil Basin, the researcher calculated the average annual recharge as follow:

$$\text{Average annual recharge }\left(m^3/\text{year}\right) = \left(\begin{matrix}\text{Volume of precipitation over the basin}\\ \left(m^3/\text{year}\right) \times \text{infiltration rate \%}\end{matrix}\right)\Big/100 \qquad (5)$$

Average annual recharge ($m^3$/year) = 1,262,880,000 $m^3$ /year × 0.2423

Average annual recharge ($m^3$/year) = 305,995,824 $m^3$/year

The amount of groundwater decline in Erbil three sub-basins are calculated as shown in Table 3

**Table 3.** Groundwater decline during (2004-2023) in Erbil three sub-basins

| Sub-basin | 2004-2023 | Area ($m^2$) |
|---|---|---|
| Northern (Kapran) | -33 | 772,000,000 |
| Central | -51 | 1,742,000,000 |
| Southern (Bashtepa) | -55 | 585,000,000 |
| Average | -46.3 | (-) means decline in groundwater |
| decline per 18 years | -2.57 | |

Table 3 showed the water level decline in each sub-basin, 33 meters, 51 meters, and 55 meters decline in Kapran, Central, and Bashtepa sub-basins respectively. The decline in the water table, based on the (55) wells that had been used as monitoring groundwater and had repeated water levels data recorded, was 2.57 m/year. This decline in groundwater was mainly due to a cluster of wells in each sub-basin, where the number of wells exceeded the legally permitted numbers. To estimate the accurate results on the groundwater conditions in the Erbil Basin, the volume of the annual water use in the basin was calculated as follows:

$$\text{Volume of the annual water use}\left(\text{m}^3/\text{year}\right) = \text{Average annual decline in the basin}\left(\text{m/year}\right)\times\text{basin area}\left(\text{m}^2\right) \quad (6)$$

Volume of the annual water use ($m^3$/year) = 2.46 m/year *3,200,000,000 $m^2$

Volume of the annual water use ($m^3$/year) =7,872,000,000 $m^3$/year

This number helps characterize the volume of water being overexploited in the region as below:

$$\text{Volume of overexploitation}\left(\text{m}^3/\text{year}\right)=\text{Volume of water used}\left(\text{m}^3/\text{year}\right)-\text{Recharge volume}\left(\text{m}^3/\text{year}\right) \quad (7)$$

Volume of overexploitation ($m^3$/year) =7, 872, 000, 000 - 305,995,824

Volume of overexploitation ($m^3$/year) =7, 580, 008, 352 $m^3$/year

To estimate the total water being pumped by the recharge using the following calculation:

$$\text{Amount of pumped water that is recharged by precipitation} = \left(\text{Recharge volume / volume of water used}\right)*100 \quad (8)$$

Amount of pumped water that is recharged by precipitation = (305,995,824/ 7, 872, 000, 000) * 100

Amount of pumped water that is recharged by precipitation =4%

To reach to sustainability, the recharge will need to increase by (96%). The sustainable recovery pumping rate is then calculated by:

$$\text{Sustainable Recovery pumping m}^3\text{/year= Volume of average annual recharge m}^3\text{/year * 90\%} \quad (9)$$

Sustainable Recovery pumping ($m^3$/year) = 305,995,824*90%

The results of this calculation indicate that, in order to keep 10% of the recharge in the basin for the purpose of basin recovery, the sustainable pumping of the groundwater from the Erbil Basin is 275,396,241.6$m^3$/year (Table 4).The values of each elements of water budget are plotted in Figure 5 (Figure 6).

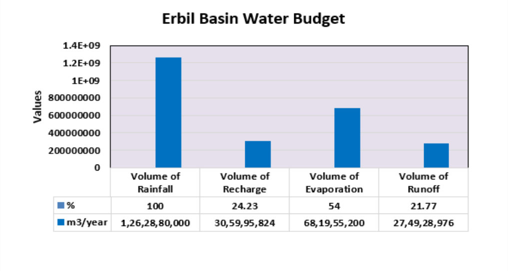

**Figure 5.** Values of estimated water budget

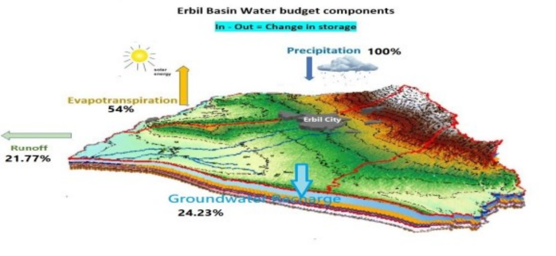

**Figure 6.** Erbil basin water budget estimation

**Table 4.** Results of the water budget elements calculations

| | |
|---|---|
| Average annual precipitation (m) | 0.39465 |
| Basin area ($m^2$) | 3,200,000,000 |
| Volume of precipitation over the basin ($m^3$/year) | 1,262,880,000 |
| Recharge volume ($m^3$ /year) based on 24.23% (Hassan) | 305,995,824 |
| Water table decline (m/year) as measured in 55 wells | 2.57 |
| Volume of annual water use ($m^3$/year) based on 2.56 m/year decline | 8,192,000,000 |
| volume of overexploitation ($m^3$/year) based on 2.56 m/year decline | 7,886,004,176 |
| Water table decline (m/year) (based on 18 years decline in water table) | 2.57 |
| Water table decline (m/year) based on calculated overexploitation | 2.46 |
| Volume of annual water use ($m^3$ /year) | 7,872,004,000 |
| Volume of overexploitation ($m^3$ /year) | 7,580,008,352 |
| Water table decline – Recharge volume | (96% of total use is overexploitation) |
| Total of the pumped water met by recharge | 4% |
| Volume of Evaporation ($m^3$ /year) (54% of total precipitation) | 681,955,200 |

### *3.2. Population characteristics and assessment of water budget*

The number of populations in study area in (1977) is (266,650), which comprises (65.9%) of total percentage of Erbil governorate populations. The population in Erbil basin in (2004) is (886,585) citizens however, in (2009) it is (1,173,036) based on the study of (Ahmad 2012), see Table 5

**Table 5.** Density of residential for years (1977-2009) (Ahmad 2012)

| Year | Population | Density (residential/ Km$^2$) |
|---|---|---|
| 1977 | 266,650 | 107 |
| 1987 | 553,038 | 221 |
| 2004 | 886,585 | 355 |
| 2009 | 1,173,036 | 470 |

The relationships between the values of each year are plotted in Figure 7

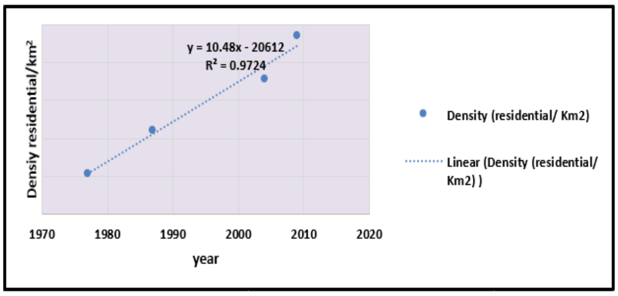

**Figure 7.** Residential density versus year in the study area

In addition, to estimate water demand for Erbil basin, the number of the population needed to be known. In order to determine the annual increment ratio, the following formula which was described in (Hassan 1998) was used:

$$r = \frac{1}{n}(\frac{P_n}{P_0} - 1) \tag{10}$$

Where:

r: annual increment ratio

$P_n$: population number in a given statistical encountering

Po: population number in prior statistical encountering

n: Number pf years between the two encountering

$$r = \frac{1}{5}(\frac{1,173,036}{886,585} \text{-}1)$$

r=0.065

In order to determine the number of populations in any time use the equation below:

$$P_t = P_o(1 + r\,t) \tag{11}$$

Where:

Pt: population number at any year in the future

Po: population number at a known year

r: population increment ratio

t: Number of years between Po and Pt

Thus, to determine population in (2023) based on year 2009 it is as follow:

Pt = Po (1 + r t)

P2023 = 1,173,036 (1 + 0.065 (14))

P2023 =2,240,499 citizens

Average daily water consumption in Erbil City was about 380 liters/Capita/day based on the data obtained from the Directorate of Water and Sewerage in the Kurdistan Region of Iraq (2023). The estimated water demand for the future long term was as shown in Table 6

**Table 6.** Estimation water demand for each year

| Year | Initial P values | demand m$^3$/year |
|---|---|---|
| 2023 | P $_{2009}$=1,173,036 | P $_{2023}$=310,757,178 |
| 2030 | | P$_{2030}$=384,785,720.4 |
| 2040 | | P$_{2040}$=490,540,781 |
| 2050 | | P$_{2050}$=596,295,841.6 |

Water based on the data available, the number of wells were about 8,342 wells based on data taken from the General Directorate of Water and Sewerage in the Kurdistan Region of Iraq (2023).

The estimated rate of well drainage for each well =25 m$^3$/hr.

The average number of operating hours for each well =15 hours.

The produced water from wells =8,342 wells (legal and recorded wells within Erbil basin)

The total quantity of water= Water treatment plants + groundwater wells

WTP= 34,000 + 44,000 +216,000 = 294,000 m$^3$/day

Groundwater wells = 8,342 wells × 15 hr × 25 m$^3$/hr = 3,128,250 m$^3$/day

294,000 + 3,128,250 = 3,422,250 m$^3$/day

The rate of loss is about 15% (General Directorate of Water and Sewerage in the Kurdistan region of Iraq, 2023).

Thus, the remaining net quantity = 3,422,250 × 85 % = 2,908,913 m$^3$/day.

Annual water consumption = 2,908,913 m$^3$/day × 365 day

= 1,061,753,063 m$^3$/year.

Thus, the lack of water supply in the Erbil Basin is water demand minus water consumption

= 310,757,178 - 1,061,753,063

= -750,995,885 m$^3$/year as the required amount of water (2023)

The negative sign indicates that there is lack of water demand.

### *3.3. Groundwater Modeling approach*

The study also estimate the sentivity analysis of the groundwater modeling. Groundwater modeling was used to estimate the water budget for Erbil basin. A three-dimensional groundwater flow model was developed using MODFLOW software. The model incorporated the geology and hydrogeology of the basin based on available data such as lithology, stratigraphy, structural features, aquifer parameters, recharge rates, etc. The model domain was discretized into grid cells and layers to represent the subsurface geology. Relevant hydrological processes like groundwater recharge, discharge, flow and storage were programmed into the model. The model was calibrated by adjusting model inputs until the simulated groundwater heads matched observed field measurements within an acceptable error range. Once calibrated, the model was used to simulate groundwater flow over time under historic pumping and recharge conditions. Key outputs of the model like annual groundwater recharge, discharge, storage changes and flows across boundaries were used to calculate the different components of the water budget for Erbil basin. The groundwater modeling approach provided a quantitative estimate of the basin-scale water budget (Al-Areedhi 2019), see Figure 8

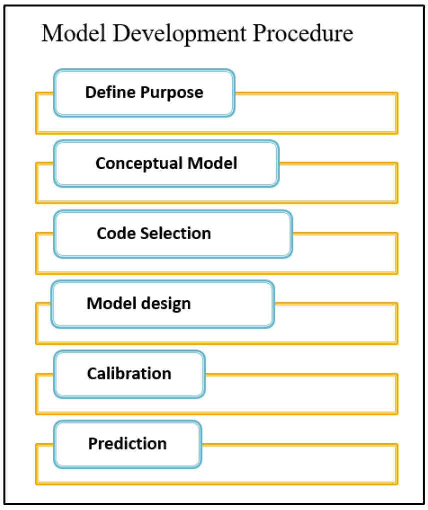

**Figure 8.** Flow chart of the study and GMS applications

In this study, the equation of steady-state heterogeneous and an isotropic is applied for the application of GMS software version 10.7. The methodology of this study can be started from collecting the data on the investigated area, which was provided by the General Directorate of Erbil groundwater and General Directorate of Water Resources, the collected information includes well data, topographic maps, number of the existing wells, and hydrogeological data. Then the raw data prepared by GIS program to be ready to input into (GMS) software for building Conceptual model. The GMS is used to simulate the steady states groundwater flow conditions using the solver package MODFLOW 2000 based on finite difference techniques (Al-Areedhi and Khayyun 2019).

$$\frac{\partial}{\partial x}(Kx\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(Ky\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(Kz\frac{\partial h}{\partial z})=0 \qquad (12)$$

Where:

K: is hydraulic conductivity ($LT^{-1}$) in (x,y,z) directions.

h: is hydraulic head (L).

### *3.3.1. Building conceptual model*

Building a conceptual model in GMS is a methodical procedure aimed at creating a comprehensive representation of the hydrogeologic conditions in a study area (Al-Areedhi and Khayyun 2019). The process commences with the input of model boundary files into the map data coverage, defining the spatial extent of the model area. Following this, the coverage is enriched by incorporating data pertaining to wells and observation head locations, crucial components that contribute valuable information to the model. Wells play a significant role in representing points of water extraction or injection, while observation heads serve to capture groundwater elevation data. In addition to these components, an additional layer is introduced to the conceptual model through a coverage that outlines boundary conditions. This layer is essential for specifying sources and sinks within the groundwater system, providing a framework to simulate the dynamic interactions influencing groundwater movement. Through the systematic integration of these components, the conceptual model in GMS becomes a powerful tool for accurately simulating and understanding the hydrogeologic complexities of the study area.

### *3.3.2. Model grid and setting boundary condition*

Once the conceptual model is established, the next step involves the creation of a 3D grid structure in GMS. This is accomplished by selecting new and then 3D Grid, followed by assigning boundary conditions in alignment with the nature of the Erbil Basin. Given the geographical limitations posed by the Greater Zab and Lesser Zab Rivers, the boundary conditions are carefully defined to encapsulate the hydrogeologic characteristics of the region. For the river boundaries, the MODFLOW 2000 Grid utilizes the river package, incorporating the specific features of the river sides into the model. Additionally, locations corresponding to groundwater divides, marked by the outcrops of geological formations, are designated as no-flow boundary conditions. The head inside the model represents the groundwater head, effectively mirroring the groundwater table observed in existing wells. Figure 9 illustrates the 3D grid structure of the model, providing a visual representation of the aquifer types and their spatial arrangement within the Erbil Basin. In addition, the detail about assigning the input data are summarized in Table 7.

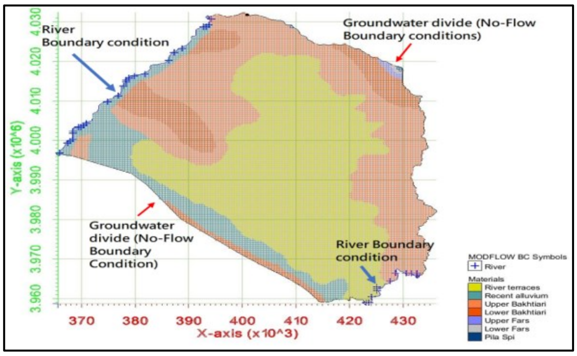

**Figure 9.** The boundary conditions used in the study

### *3.3.3. Create new simulation (MODFLOW) steady-state conditions*

The transition from the conceptual model to the MODFLOW simulation involves a critical step of mapping the relevant parameters. This process includes the interpolation of the top and bottom of the model layer onto the 3D grid. All coverages in the conceptual model are converted using the map to MODFLOW tool, facilitating a seamless integration of the conceptual model into the numerical simulation. The top of the model grid corresponds to the natural groundwater surface, represented by a Digital Elevation Model (DEM) with a resolution of cell sizes set at (28 × 28) meters. This DEM essentially serves as a topographic map of the Erbil Basin, providing a precise depiction of the surface elevation. Notably, the bottom of the 3D grid aligns with the depth of the drilled wells, capturing the subsurface configuration (Al-Areedhi and Khayyun 2019). The model, showcased in Figure 10, effectively delineates the characteristics of the unconfined aquifer types within the Erbil Basin, emphasizing the importance of accurate mapping for a comprehensive representation in groundwater simulations. In addition, based on the formation types within Erbil basin, the values of the Hydraulic conductivity obtained from the following Table 8.

**Table 7.** Input data for MODFLOW 2000 package in GMS software

| Conceptual model | Descriptions of the items |
|---|---|
| Model domain | Cell sizes (100 by 100) m by 700 m depth of the aquifer |
| Boundary condition | River conductance (2.74 and 2.29) $m^2/d/m$ for Greater and lesser Zab rivers respectively |
| | Greater Zab River U/S node GZ= (279 m and 277m) and D/S node GZ= (215 m and 213 m)<br>Lesser Zab River U/S node LZ= (270 m and 268m) and D/S node LZ= (252 m and 250 m) |
| Aquifer types coverage | Define each of the material’s hydraulic conductivity in LPF package |
| Recharge Coverage (RCH) | The polygon of the model area defined by (RCH=0.000385 m/day) as initial values including (10%-40%Avegarge annual rainfall) + surface water bodies |
| Existing wells coverage | Number of the wells (8384 wells) + (55 observation wells) |

**Table 8.** The Hydraulic conductivity ranges (Freeze and Cherry 1979).

| Descriptions of the rock types | K min (m/day) | K max (m/day) |
|---|---|---|
| Unconsolidated deposits | | |
| Coarse gravel | 864 | 8640 |
| Sands and gravels | 0.864 | 864 |
| Fine sands, silts | 0.0000864 | 0.864 |
| Clay, shale, glacial | 8.64E-09 | 0.0000864 |
| Hard rocks | | |
| Dolomitic limestone | 0.864 | 86.4 |
| Weathered chalk | 0.864 | 86.4 |
| Limestone | 0.0000864 | 0.0864 |
| Sandstone | 0.00000864 | 8.64 |
| Granite, Gneis, Compact basalt | 8.64E-09 | 0.0000864 |

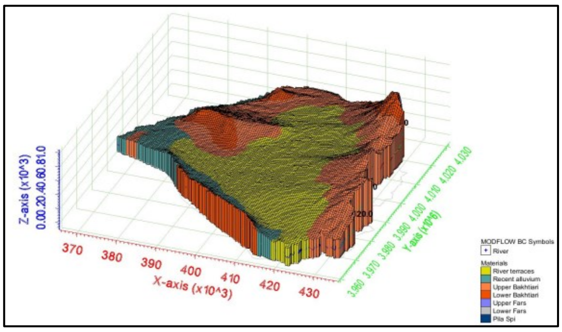

**Figure 10.** the Model structure of the Aquifer types (geological formations)

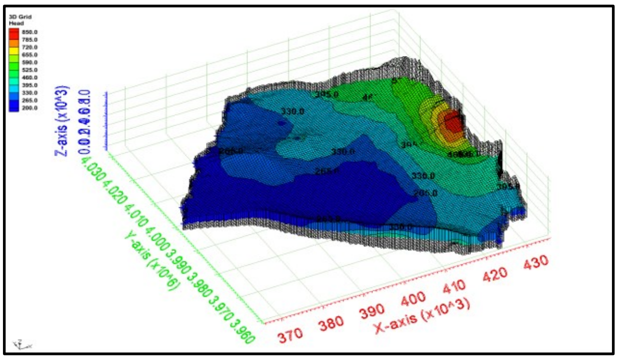

**Figure 11.** The contour map of groundwater flow head

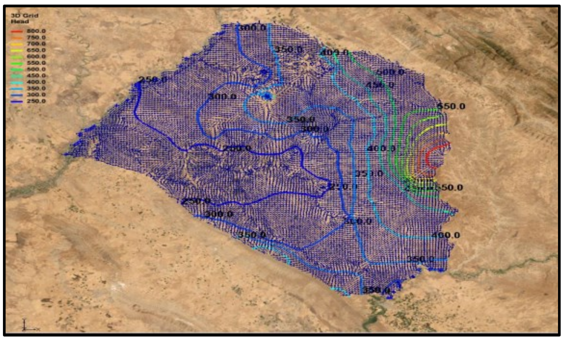

**Figure 12.** Distribution of the velocity vector over the model area

### *3.3.4. Run steady-state model*

The calibration process in groundwater modeling involves adjusting model parameters to align calculated results with observed hydraulic patterns of groundwater flow. This adaptation is crucial for ensuring that the model accurately represents the real-world behavior of the aquifer system. Key elements in the calibration process include measured head values and local flow directions, often derived from interpolations of head measurements to create contour lines of the groundwater surface (McDonald *et al*. 1988). In the case of the Erbil model, the flow direction and associated heads are intricately linked to the morphology of the layered aquifers. Despite the presence of a significant number of observation wells distributed across the model domain, common interpolation methods prove to be challenging in accurately representing water table characteristics due to the complex nature of the aquifer system. The limitations of these methods are highlighted in Figure 11, underscoring the need for a thoughtful and context-specific calibration approach in capturing the nuances of groundwater flow in the Erbil Basin. Whereas, the velocity vector obtained from the model results are Figure 12.

### *3.3.5. Calibration steady-state model using PEST pilot points*

The primary objective of model calibration is to reduce the disparity between observed and simulated head values by fine-tuning model parameters. Achieving this alignment is crucial for ensuring that the model accurately reflects the actual behavior of the groundwater system. Calibration can be carried out through manual adjustments via trial and error, or more systematically through automated approaches like parameter estimation using PEST pilot points in GMS. The effectiveness of calibration relies on the thorough characterization of field conditions at the site (Al-Areedhi and Khayyun 2019). Proper understanding and representation of the hydrogeologic setting are essential for refining model parameters to attain an accurate simulation. In the Erbil model, the results of the calibration process demonstrate a harmonious match between observed and simulated head values, as depicted in Figure 13, indicating the success of the calibration in capturing the intricacies of the groundwater flow in the studied area.

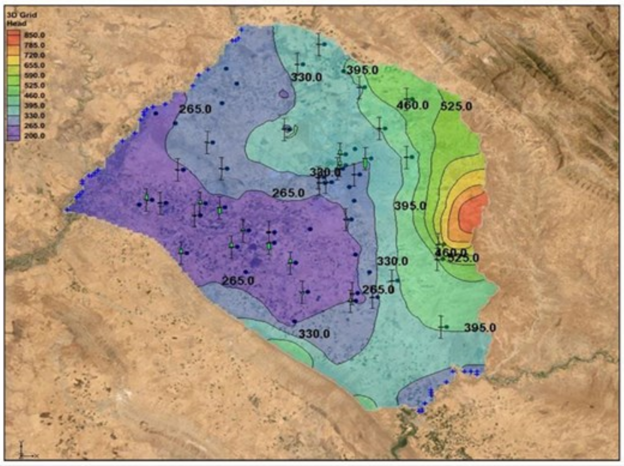

**Figure 13.** The calibrated groundwater head

Following the model run, it is common for the obtained results to exhibit variations from the actual field values. This disparity is inherent in modeling, given that it involves simplifications of the complex physical behaviors of reality, and allowances are made for approximations and computational errors. The critical step of model calibration is undertaken to minimize these differences and align the model results with the actual field values (Al-Areedhi and Khayyun 2019). In groundwater modeling, achieving concordance between the resulting observed head and the simulated head at corresponding points is essential. This calibration process involves adjusting model parameters, such as hydraulic conductivity (HK) or recharge (RCH), to optimize the match between the model's predictions and the observed field data. Through a systematic adjustment of these parameters, the calibration process seeks to enhance the model's accuracy, ensuring that it captures the nuances of the groundwater flow in the studied area.

The calibration process is very important to represent the actual behavior of the model. To perform this process, consider the observed groundwater head as (h observed)i at the observation point (i), and the calculated head at the same point is (h simulated)i, The root mean square error (RMSE) equations are:

$$\text{Mean Error equation: } ME=\frac{1}{2}\sum_{i=1}^{n}(h_{observed}-h_{simulated})_i \tag{13}$$

$$\text{Mean Absolute Error:} MAE=\frac{1}{2}\sum_{i=1}^{n}/\ h_{observed}-h_{simulated}/_i \tag{14}$$

Root Mean Square Error: (15)

$$RMSE=\sqrt{\frac{1}{2}\sum_{i=1}^{n}(h_{observed}-h_{simulated})_i^2}$$

The final step in the groundwater modeling process is model validation, which occurs subsequent to the calibration phase. The primary objective of model validation is to assess the general performance of the calibrated model on datasets distinct from those used in the calibration process. Calibration involves adjusting various parameters, such as hydraulic conductivity (HK) and recharge (RCH), and different combinations of values can yield similar solutions. The validation process is crucial in determining the broader applicability of the calibrated model beyond the specific dataset used for calibration (MacDonald *et al*. 1988; Anderson *et al*. 2015; Al-Areedhi and Khayyun 2019). Typically, modelers divide the acquired data into two sets: one for calibration and another for the validation process. By employing independent datasets for validation, modelers can rigorously assess the model's robustness and reliability, ensuring that it provides accurate and consistent results across different conditions. See Figure 14.

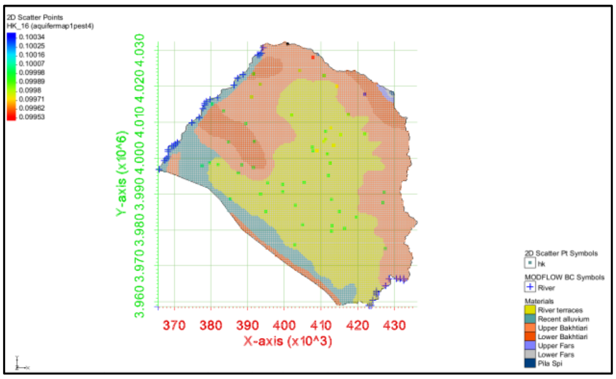

**Figure 14.** The 2D scatter points in the active grid for calibration PEST Pilot points

In this study, the minimization of errors in the groundwater model was achieved through the application of PEST pilot points, particularly for hydraulic conductivity values sourced from various pumping test results. PEST, a widely used parameter estimation tool, allows for a systematic adjustment of model parameters to optimize the agreement between simulated and observed data. By incorporating data from pumping tests and leveraging PEST pilot points, the study aimed to enhance the accuracy of hydraulic conductivity values in the calibrated model.

The results of this application of PEST, which encapsulate the refined hydraulic conductivity values, are succinctly summarized in Table 9. This table serves as a comprehensive compilation of the outcomes of the parameter estimation process, providing a clear representation of the adjusted model parameters achieved through the iterative application of PEST methodology.

**Table 9.** The values of Errors in PEST application

| Descriptions | Symbol | Values |
|---|---|---|
| Mean Residual (Head) | ME | -0.03 |
| Mean Absolute Residual (Head) | MAE | 0.24 |
| Root Mean Squared Residual (Head) | RMSE | 0.36 |

The Figure 15 depicts a comparison between computed and observed head values derived from the model results. This graphical representation provides a visual assessment of the accuracy and agreement between the simulated groundwater levels produced by the model and the actual observed head values from the field. Analyzing the relationship between computed and observed head values is crucial for evaluating the model's performance and its ability to replicate real-world hydrogeologic conditions. The closer the points align to the line in the Figure 15, the better the model's predictive capability, indicating a successful calibration and validation process.

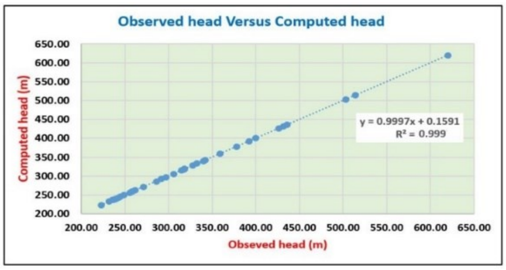

**Figure 15.** Plot of the observed head versus simulated head

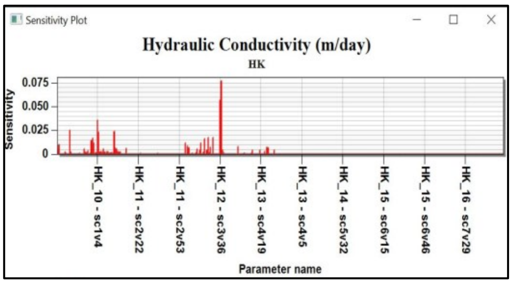

**Figure 16.** Parameter Sensitivity of the Hydraulic conductivity values used for PEST pilot points

### 3.3.6. *Sensitivity analysis*

The sensitivity analysis is performed to compare between model results and parameters for case of before and future periods of the calibration. It can be determined by fixing all the calibrated parameters except of the selected parameter, this indicates which parameters have greater impact on the model results. Parameters have high impact on the model results should get the most attention in the calibration process and data collection. In addition, the most common method of sensitivity analysis is the use of finite difference methods to estimate the rate of change in model results due to change in the parameter (Mac Donald *et al.* 1988; Anderson *et al.* 2015; Al-Areedhi and Khayyun 2019). This study used the trial and error methods, then Automated Parameter Estimation (PEST)and PEST Pilot points to optimize the parameter values as shown in Figure 16.

**Table 10.** Water budget information obtained from steady state Run in GMS

| | Flow In | Flow Out |
|---|---|---|
| Sources/Sinks | | |
| Constant Head | 0 | 0 |
| Wells | 0 | -963,959.40 |
| River Leakage | 0 | -194,677.92 |
| Recharge | 1,158,637.37 | 0 |
| Total Source/Sink | 1,158,637.37 | -1,158,637.32 |
| | | |
| Zone Flow | | |
| Flow Right Face | 0 | 0 |
| Flow Front Face | 0 | 0 |
| Flow Left Face | 0 | 0 |
| Flow Back Face | 0 | 0 |
| Total Zone Flow | 0 | 0 |
| | | |
| Total Flow | 1,158,637.37 | -1,158,637.32 |
| | | |
| Summary | In - Out | % difference |
| Sources/Sinks | 0.050743103 | 4.38E-06 |
| Cell to Cell | 0 | 0 |
| Total | 0.050743103 | 4.38E-06 |

### *3.3.7. Water budge*

The water budget analysis is a pivotal aspect of understanding the hydrologic dynamics within the modeled region. In this study, the GMS software facilitated the computation of water budget results, shedding light on the inflow and outflow components in the model. The quantity of recharge, representing water inflow, is a critical parameter that influences the groundwater system's sustainability. Concurrently, the outflow is determined by considering factors such as production water wells and rivers, representing losses from the system. The GMS output provides a comprehensive overview of the water budget, encapsulating the intricate balance between inflow and outflow in the model region. The results, as summarized in Table 10, offer valuable insights into the overall water dynamics, enabling a nuanced understanding of the groundwater movement and sustainability within the studied area. This information is crucial for effective water resource management and informs decision-making processes related to the sustainable use of groundwater in the region.

Table 10 provides a comprehensive breakdown of the water budget for the Erbil basin, offering valuable insights into the quantity of water entering and leaving the aquifer. This data holds significant importance for local authorities as it forms the cornerstone for informed decision-making regarding water resource management. Understanding the dynamics of water inflow, represented by recharge, and outflow, including water extracted from production wells and contributions from rivers, is crucial for ensuring the sustainability of this vital resource. The information presented in the table serves as a foundational tool for authorities to plan and implement measures that will safeguard the groundwater reserves for future generations. In regions prone to drought problems, such as the Erbil area, this data-driven approach becomes even more critical. It equips authorities with the knowledge needed to address challenges related to water scarcity, enabling the formulation of strategic and sustainable solutions to mitigate the impact of drought and secure a resilient water supply for the community.

## 4. Results and discussion

The results of this study showed that the groundwater declined during the periods of (2004-2023), and this decline was calculated by adding the average decline in each sub-basin and dividing the result by three, so this gave the average decline in 18 years, dividing it by 18 gave the average decline in a year. Multiplying the 2.57 m/year decline by the basin area gave the average volume of annual water used in the basin, which was 8,192,000,000 $m^3$/year. The annual water use volume subtracted from the recharge volume (310,757,178 $m^3$/year) gave overexploitation volume in the basin, which was (7,886,004,176) $m^3$/year. Dividing the volume of average annual overexploitation (2,185,833,980 $m^3$/ year) by the basin area gave 2.46 m/year water table decline due to overexploitation in the basin. All of the calculations were based on a 2.46 m/year decline. To double check it, the volume of annual water use and overexploitation were recalculated based on a 2.46 m/year decline. The sustainable pumping volume for the basin was equal to the average annual recharge of the basin, which was (310,757,178 $m^3$/ year). This volume represented what should be extracted from the Erbil Basin instead of (7,580,008,352 $m^3$/year). Furthermore, because the groundwater levels in Erbil Basin were facing a serious depletion, the author also calculated a recovery pumping rate, which required that a portion of the average annual recharge would not be pumped from the basin so that the basin could start to recover and the water table would slowly rise to earlier levels. The study compared the obtained results with the previous studies that investigated within particular location inside the region the values are close to each other.

The study identifies a lack of groundwater management in the region, primarily due to overexploitation of subsurface water resources. Employing GMS software with MODFLOW 2000 solver, the three-dimensional groundwater flow model provides valuable insights into the aquifer system of the unconfined aquifer in Erbil basin, Kurdistan region, Iraq. The study concludes that average groundwater recharge values range between (0.000375-0.00037597459) m/day. Model calibration utilized trial and error, automated methods, and PEST pilot points, demonstrating a mean residual error (ME) of -0.03, mean absolute error (MAE) of 0.24, and root mean square error (RMSE) of 0.36. The coefficient of determination ($R^2$) of 0.999 underscores the model's excellent correspondence with field observations. Additionally, the average groundwater flow velocity is estimated at approximately (0.008459) m/day, aligning with values reported in comparable studies conducted in the region. Overall, the study contributes to a comprehensive understanding of groundwater dynamics in the Erbil basin, emphasizing the need for sustainable water management practices.

## 5. Conclusion

The hydrological study was carried out on Erbil basin region, which covered an area of about 3200 $Km^2$. From the results obtained in the water budget assessment for Erbil basin, the long-term observations of the following hydrological parameters had been estimated for the periods of 25 years, then each element of the precipitation, the evaporation, and surface runoff had been computed. Meanwhile, the amount of the water demand for the present and future years also was estimated. The study concluded that there was a lack in water demand in the study area, which was mainly due to increasing population density and their requirement for water consumptions, the research also assessed that the poor management and the rate of input data was much less than the water that was pumped out from the aquifers in the area, which led to producing less amount of water availability than the people's requirement for water. The continuous overexploitation of the amount of groundwater without management would cause water scarcity and drought problems in the near future. At the end of the study, it was highly recommended that the water resources in Erbil basin needed to be kept sustainable and developed for future generations and to follow the steps of sustainability. The hydrological study and assessment of the water budget for the Erbil Basin would provide valuable insights into the availability, distribution, and sustainability of water resources within the basin, guiding decision-making for water resource management and planning. These were all the main goals of the present investigation, which had been to study the hydrological data from the Erbil catchment area in the northern part of Iraq and apply the budget equation to evaluate the basin conditions. This had been conducted possible by a systematic hydrological study that had been carried out in the research area. The study successfully demonstrated the capability of GMS software in accurately simulating groundwater levels within the Erbil basin. However, it acknowledges several limitations that impact the depth of understanding of the aquifer system. The primary challenge lies in the lack of comprehensive data, particularly the absence of dedicated observation wells, as all monitored wells serve production purposes. This limitation hampers the ability to precisely verify the actual groundwater table within the model region and highlights the scarcity of essential system properties.

**Acknowledgement**

This paper is apart of the phd study that is conducted on Erbil basin

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