The Determination of Ground Water Balance (GW) Using Modeling Flow, A Case Study West of Karbala Province

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Abstract

Water shortage is one of the serious environmental problems in a semi-arid region, which has become increasingly dangerous. The article considers a new management simulation model of Groundwater (GW) resources using a water flow model. One thousand one hundred fifty irrigation wells were selected as a study area using Landsat 8 OLI images 2016-2021 in the West of Karbala province, Iraq. Geographic Information System tool integrated with numerical /conceptual model using the Visual MODFLOW Flex 7 software to reach the optimal use of GW resources. The conceptual model indicated that the value of the flow in the aquifer reaches 21 million cubic meters annually, which means there is renewable storage. The consumer value of GW was about 55 million m3/year. The result presented that the value of the lost and depleted storage in this part becomes about -34 million m3/year, which is the value of the variation in the underground storage, meaning there is a significant depletion of GW in the study area. Using the Visual MODFLOW Flex 7 software and entering parameters for the study area through pumping and monitoring wells, an error of 0.067 m was achieved in estimating groundwater recharge places near the folds' rocky aquifers. The normalized RMS for the model was 69.595%, and the correlation coefficient was 0.391. The contour lines in the region's East indicate increased conductivity due to channels and openings formed during groundwater-bearing rocks, depressions, and lakes. The study concluded that the outputs could help water administrations for more accurate and sustainable plans and management of GW resources in the Karbala area.

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حساب الموازنة المائية للمياه الجوفية باستخدام نموذج التدفق المائي حالة دراسية/غرب محافظة كربلاء

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الخلاصة

من المشاكل البيئية في المناطق القاحلة وشبه القاحلة هي النقص في الموارد المائية، والتي أصبحت خطيرة بشكل متزايد نظرا للتغيرات المناخية والنقص الحاد في المياه السطحية. تتناول الدراسة نموذج محاكاة إدارة لموارد المياه الجوفية حيث تم تحديد 1150 بئراً للري باستخدام صور لاندسات ذو المتحسس OLI خلال الفترة 2016−2021 في منطقة الدراسة الواقعة غرب محافظة كربلاء جنوب غرب العراق. تم استخدام نظم المعلومات الجغرافية مع النموذج العددي / المفاهيمي من أجل الوصول إلى الاستخدام الأمثل لمورد المياه الجوفية في منطقة الدراسة، حيث تم استخدام برنامج Visual MODFLOW Flex 7 وإدخال معلمات الخزانات التحت سطحية لمنطقة الدراسة من خلال آبار الضخ والمراقبة. أشارات نتائج النموذج الحالي إلى أن قيمة التدفق في الخزان الجوفي تصل إلى (21) مليون متر مكعب سنويًا، مما يعني أن يوجد مخزون متجدد، كما تم حساب القيمة الاستهلاكية للمياه الجوفية، وبلغت حوالي (55) مليون م 3 / سنة. أظهرت النتيجة أن قيمة الخزن النوعي والمستفد في هذا الجزء بالذات حوالي (34−) مليون م 3 / سنة، وهي قيمة التباين في التخزين الجوفي، أي أن هناك استغلال كبير للمياه الجوفية. في منطقة الدراسة. ، كشفت نتائج المعايرة بين القراءات الحقلية لمياه الابار والقراءات التي اوجدها النموذج المفاهيمي في تقدير أماكن تغذية المياه الجوفية بالقرب من الخزانات الجوفية أن نسبة الخطأ القياسي في التقدير للنموذج بلغ 0.067% وأن الجذر التربيعي المتوسط للخطأ RMS كان 0.263 ومعامل وثوقية confident interval تصل الى 95٪ . خلصت الدراسة إلى أن النتائج يمكن أن تساعد سلطات المياه في تخطيط وإدارة أكثر دقة واستدامة لموارد المياه الجوفية في منطقة كربلاء.

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1. Introduction

Population increase has placed ever-increasing demands on the available groundwater (GW) resources, particularly for intensive agricultural activities [1]. The substantially increasing population, industrial growth, and random urbanization caused rising demand for water resources such as groundwater (GW). GW is a valuable resource in semi-arid areas such as the eastern and western parts of the Iraqi Western Desert, where rivers, lakes, and precipitation are few or unreachable because of climate change. GW supplies many of life's needs and utilizes in several applications like industrial, agricultural, and other purposes.

GW depletion, defined as long-term water-level decreasing caused by repetitive withdrawals of GW continuously, is a main issue accompanied by GW use. Many regions of Iraq are suffering from GW depletion, such as the Karbala province. Groundwater is the main source of drinking water for about 50% of the population and mostly all of the rural population, and it provides over 50,000 million gallons per day for agricultural needs [2,3]. The purity and quantity of groundwater resources direct to decline and depletion, and the sustainable management of GW and simulated optimization aspects are vital to the high increase of water need.

The optimization models are formulations described mathematically by the function and a group of constraints arranged to obtain better solutions lining the considered goal. The utmost management models of the aquifer can find the objectives of the ruling equation of GW flow that coincide with optimization methods [3,4]. Additionally, studies of simulation, linear, nonlinear, and dynamic programming are the common programming methods; for example, Das and Datta [5] presented comparative research on the computational difficulties and

applicability of many of these models. It was explained that the wells dug in this region partially penetrated this formation. The general direction of the GW movement is from the west and southwest to the east and northeast towards the Al-Razzaza Lake Basin, that is, in the direction of the slope of the layers [6] (Figure 1), Al-Ghanimy [7] prepared a study on the hydrogeology of GW for Al-Dammam formation in the west and southwest of the city of Karbala, and appointed the root, beginning and lifetime of the GW on both sides of the Abu Al-Jer Fault. Al-Shammari [8] conducted a study to assess the quality of the GW of the Dammam Formation on both sides of "Tar Al-Sayed" and made a water balance for the reservoir, showed that the quality of the GW of the western part of the Dammam Formation is better than the eastern part of the Karbala-Najaf plateau. The western and southwestern parts of the Karbala province are considered among the desert areas known for a shortage of surface water and minimum yearly rainfall, which is not more than 100 mm yearly, with a high rate of evaporation [3,9].

Moreover, the type of deposits in the area contains sandy soil that does not retain water for a long time. Therefore, all economic activities, agricultural, industrial, human consumption, or animal drinking, depend on GW. Many studies found that the formation in this area is characterized by abundant and renewable GW suitable for most crops and other economic activities [10,11].
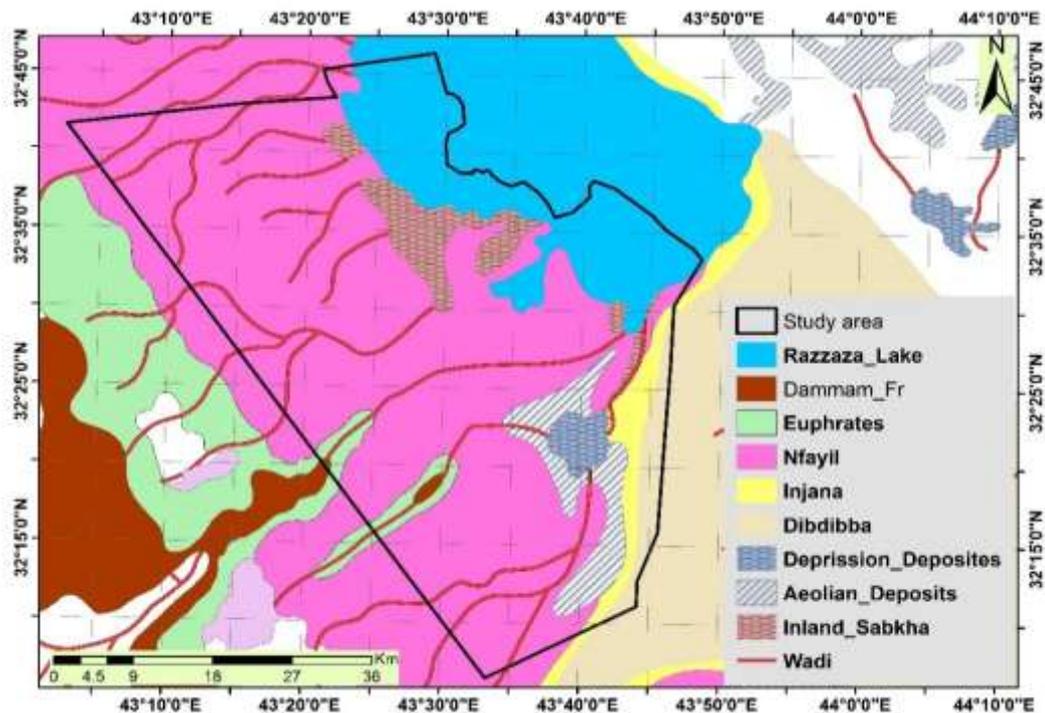
Figure 1: The geology of the study area [12]

The study area contains many geological formations, including Tayarat, Umm Er-Dhuma, Dammam, Nyfile, and Euphrates, representing water-bearing parts of the Karbala desert. Al-Shammari, [6] mentioned that the Dammam is a confined aquifer and is considered the main hydrogeological produced unit in this region

Water balance is an essential tool in hydrological and hydrogeological studies, and it is the method of calculating the amount of water obtained and consumed for a certain period, and it is also possible to determine the values of water needs. Water balance application deals with large areas and can be implemented for long periods, especially in areas without rainfall

fluctuation [6]. Rainfall and surface runoff through valleys are the main inputs to the water balance, while evaporation and withdrawal of GW by wells are the main outputs [7]. Al-Razzaza Lake is a natural drainage area for surface water flowing through valleys [6]. This study aims to determine the water balance for the area under study and the quantity of exploited and renewable GW for the best sustainable management.

1.1 The hydrology of the Study area

It is about 100 km south of Baghdad, representing a rural Karbala province region. The study area is located southwestern of Razzaza Lake from the north to Al-Najaf province boundaries in the south, located between 32°48′–32°00′ (latitude) and 43°00′–43°48′ (longitude) and a total area is 2743 km^2. Using the satellite image is initially selected in the map grid of Iraq. Then it was displayed using the software Arc-Map 10.5 on a GIS environment, Figure 2. In recent years, from 2016 to 2021, there has been a vast demand for establishing farms to produce Hordeum vulgare and Zea mays. The locations of 1150 wells are shown in the satellite images (Landsat OLI, 17/3/2021) obtained from the USGS [13]. In addition to the extensive agricultural activity in this part, there are about 83 wells dug for industrial purposes, such as the factories of washed sand and crushed gravel, and 52 wells of the Al-Saqi project for alternative water (in the situation of the drought of surface water), thus the total number of wells in the area reached to 1285 wells.
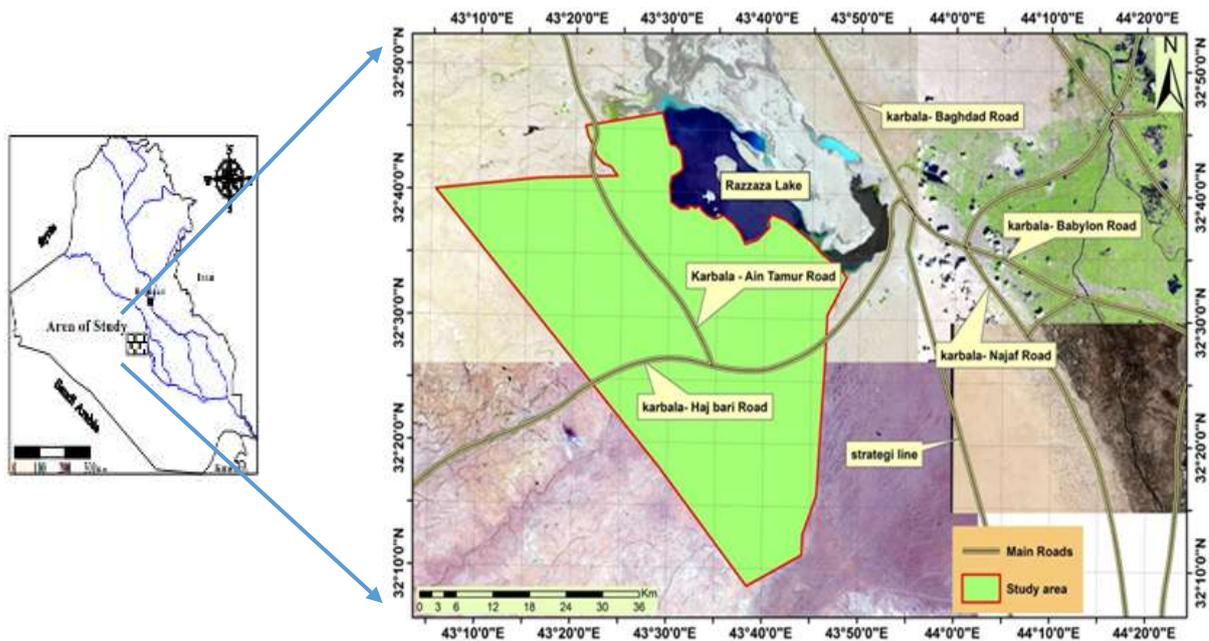
Figure 2: Study area map

1.2 Geology of Study Area

The area has rock types, claystone, siltstone, sandstone, and sandstone, with silt layers of chalky limestone [11,9]. The study area is presumed to be a tiny piece of the Najaf-Karbala plateau in central Iraq, a component of the larger Mesopotamia region. Gypcrete deposits practically entirely cover the study region. The lithology profile was founded on the results of 40 wells dug by the General Commission of GW in Iraq (GCGW, 2020) and on extra coring conducted well inside the bounds of the study region. According to wells dug by GCGW [14,15], the rock samples were obtained from the layers sections of these wells. The sequence stratigraphy of the study area from deepest to highest Figure3 follows.

1. The Formation of Dammam (Eocene),
2. The Formation of the Euphrates River (Early Miocene),

3. The Formation of the Nfayil (Middle Miocene),
4. Injana (Upper Miocene),
5. Dibdibba Formation (Pliocene–Pleistocene).

The old layers of the Dammam formation consist of limestone, agglomerated limestone, and marly limestone. These formations comprise various carbonate rocks, mostly dolomite, dolomitic limestone, and limestone, as well as marl and evaporate [3]. It is possible to regard the Al-Dammam formation, which dates back to the Eocene epoch, as one of the most significant formations of aquifers in the southwest desert [10]. The second formation is the Euphrates Formation (Early Miocene), which consists of chalk limestone, recrystallized limestone, and marl lenses. The Nafa (Middle Miocene) is formed following these layers, composed of a sandy, dolomitic, and gypseous green marl with interbedded calcareous, fossiliferous limestone, and partly sandy claystone. In specific locations, the sandy marl has a reddish hue. Gypsum can be found within the rocks as selenite veins and crystals [15-17]. Injana (Upper Miocene) and Dibdibba Formation (Pliocene–Pleistocene) are the last two formations. BoSayid and Tar Al-Naja ridges expose straight the Injana formation and in Al-Razzaza Lake's eastern beach. The formation generally has red, partly greenish silty, sandy calcareous claystone and lentils of grey, brownish, greenish, and yellowish sandstone [2, 3, 18-20].

1.3 Groundwater Aquifer
Some geological formations are water carrier formations in the Karbala desert [3]. Figure (3) shows the keyhole positions and all wells utilized to obtain an Al-Dammam extension and thickness. Figure (4) shows the equipotential contour map for the regional study area. The main direction of GW flows across the east and the northeast. Most of the well designs in the region line the well between the depth 24-36m with iron pipes and name the sides of the well to isolate the upper layers with poor GW from forming the Dammam reservoir layers [15].
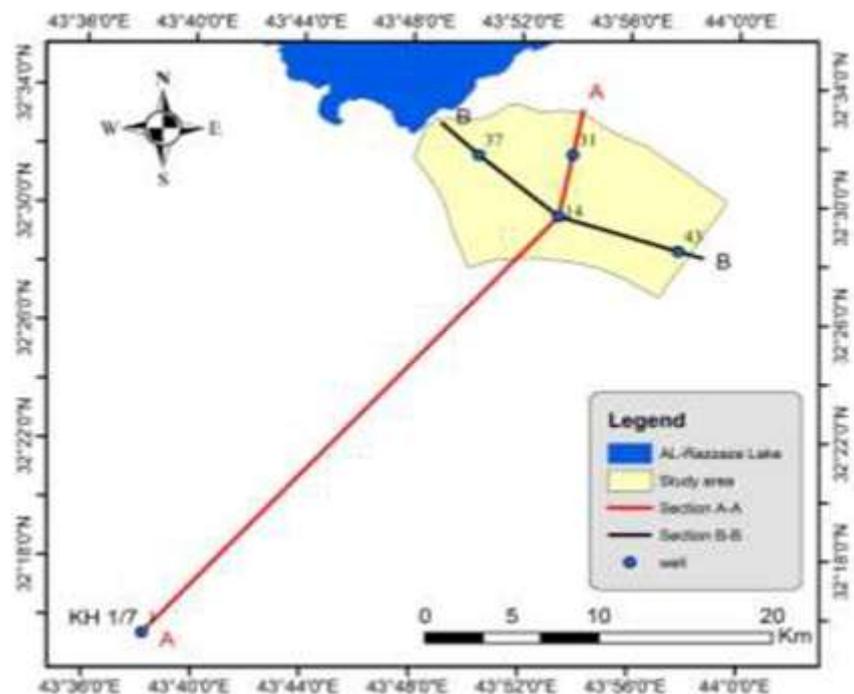
Figure 3: Trend of the sections between the wells in the study area
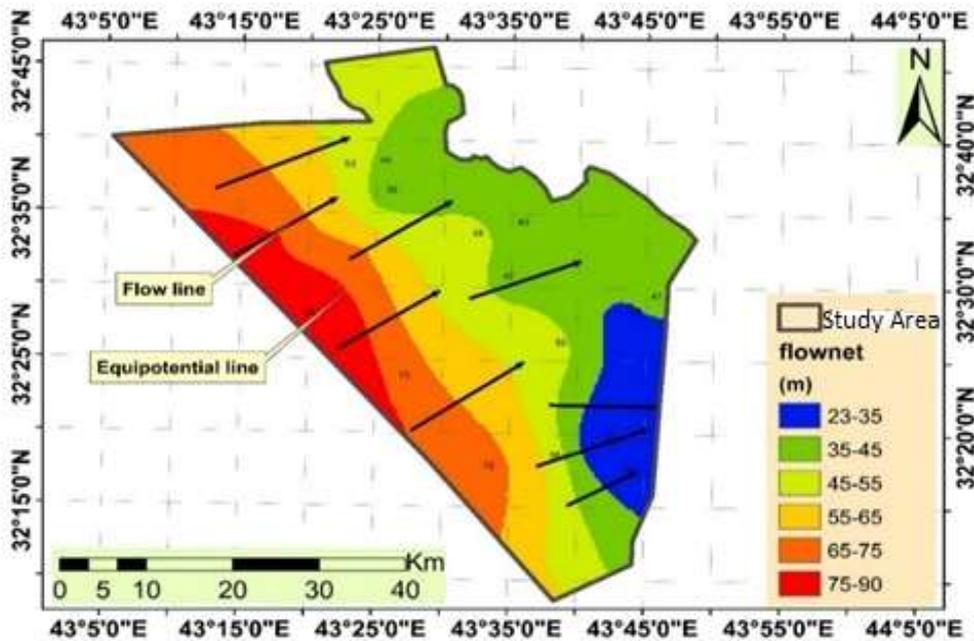
Figure 4: Map of the general trend of GW in the region

2. Material and Methodology

To calculate the water balance of the study area, several satellite images (Landsat8) and a digital elevation model (DEM) layer [21] were downloaded from the US Geological Survey website. http://www.usgs.gov, for six years, 2016, 2017, 2018, 2019, 2020, and 2021. The satellite scene Path:169 and Row:38 and Path:169 Row:37. Data processing was done using the GIS program (Figure 2). The Fluorimeter was used for each of the activities, expenditures, and the number of pumping hours, and the flow charge of the wells.

The calculation of the amount of exploited and renewable GW for the study area was done based on the water balance equation of (Domenico and Schwartz, 1998) as follows:

$$\Delta S = Q_{in} - Q_{out} \ldots\ldots\ldots\ldots\ldots \qquad \ldots (1).$$

Where: ΔS = Variation in the amount of underground storage (m^3/year).
Q_{in} = the amount of GW entering the reservoir (m^3/year).
Q_{out} = the amount of GW extraction from the aquifer through wells (m^3 / year).
 subsurface inflow
The value of the subsurface runoff entering the study area can be calculated using Darcy's equation, as stated in [22, 23].

$$Q_{in.\ Total} = TIL \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2).$$

Where:
$Q_{in.\ Total}$ =Discharge in units (m^3/day), T =conductivity in units (m^2/day), I =hydraulic slope (without units), L =width of the subsurface flow front entering the study area in units (m).

2.1 Water Flow Model

Numerical modeling technology has been essential in GW studies in reflow years. Many visual numerical modeling software of GW based on various processes was developed and highly implemented, such as the Finite Element subsurface FLOW system (FEFLOW) [20] GW modeling system (GMS) [24]. Visual Modular three Dimensional Flow (Visual MODFLOW) [23], a 2D and 3D geostatistics, uncertainty analysis, and visualization software

package [23]. MODFLW is widely used as a calculating software because of its easy procedures, modular program structure, and distinct package to answer unique hydrogeological issues. For example, GMS's popular tools, Visual MODFLOW, are all based on the MODFLOW application. They offered an excellent graphical interface for users by combining GIS technology, and they played a significant role in the evaluation and management of GW in many nations. Many 2-D or 3-D GW flow quantity and quality models have been effectively created to handle various GW flow challenges [3, 24, 25, 26, and 27].

3. Result and Discussion

The Modflow model was created without GW abstraction under natural GW flow conditions. According to the DEM map from the US Geological Survey website, the topographic of the study area ranges between 25 and 157m above sea level with accuracy (30×30 m), Figure 5. The model was then calibrated using current water level data from the area by running a steady-state model. The steady-state simulation findings were then used as the initial conditions for an unsteady state simulation, considering the existing 16 wells as indicated in Tables (1-3) and Figure 6. The simulations were run for a year to see how much GW was drawn down.
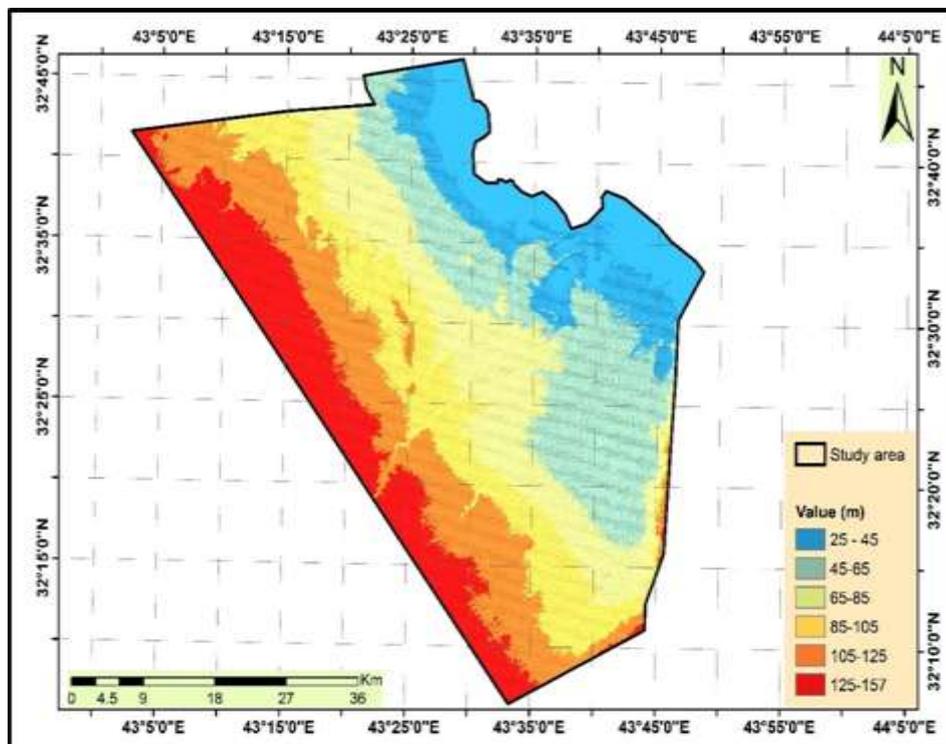
Figure 5: Topography of the study area and U.S.G.S. DEMs

3.1 Grid Design

The model's zone covered about 2743 km^2; a grid was chosen for the model consisting of one layer, 57 columns, and 45 rows. This portioning creates 2565 cells in the active and inactive of the model.

3.2 GW Recharge (GWR)

It was found that the outcrops of carbonate rocks cover most of the area, and these outcrops, especially in the upper basin, represent recharge areas for aquifers. The total annual mean of rainfall was found to be 161mm. The groundwater recharge (GWR) value was about 43.15mm/year, representing 26.8% of the total rainfall [6].

3.3. Constant-head boundary

Steady boundary conditions were used to constrain GW flow conditions in the modeled domain, established in a fringe zone far enough from the well field to limit effects on simulated heads within the model domain [7].
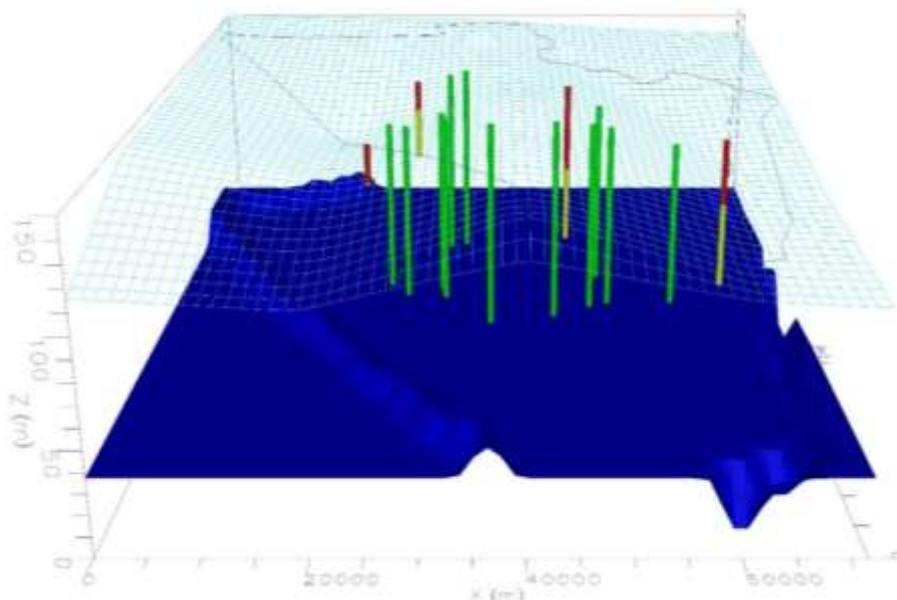
Figure 6: The location of the wells in the study area

3.4 Storage coefficient

An initial evaluation of the storage coefficents was needed for unsteady simulation in the confined aquifer and used as input data for the Modflow model.

3.5 Hydraulic conductivity

The Dibdibba aquifer, which extends from the Karbala–Najaf plateau and encompasses an area of 1100 km^2, is the study region's uppermost unconfined aquifer. Seasonal flow streams from direct rainfall within the Plateau feed the aquifer. The seasonal flow stream is directed 40 degrees northward toward the Mesopotamian Basin [11]. Initial values of aquifer hydraulic conductivity for confined aquifer were evaluated from pumping test results of wells within the studied area. These values were utilized as initial parameter values of the model. Hydraulic conductivities are 1.07 to 21.11 m/day [6].

Table1: Hydrogeological properties for monetary wells in the study area

Well No.	X coordinate	Y coordinate	ID	elevation (m)	head	Total depth(m)	H.K.(m/day)
1	374,142.10	3,589,690.16	A	18.7	69.01	90	11.09
2	366,733.75	3,589,478.50	A	18	89.4	85	11.09
3	365,887.09	3,596,886.85	A	21	113.4	110	11.09
4	364,617.08	3,588,631.83	A	19.7	99	120	11.09
5	360,383.74	3,586,091.82	A	20.5	59.06	120	11.09
6	350,012.05	3,607,258.53	A	22	126	181	11.09
7	348,107.05	3,606,411.86	A	19	98	121	11.09
8	353,187.06	3,584,398.49	A	18	91.2	196	11.09
9	347,895.38	3,591,171.83	A	20	125	100	11.09
10	347,472.05	3,593,500.17	A	21	96.3	100	11.09
11	343,450.37	3,591,806.83	A	22	92.4	134	11.09
12	341,333.70	3,594,558.51	A	19	91.7	190	11.09

Table 2: Hydrogeological properties for pumping wells in the study area

Well No.	X coordinate	Y coordinate	ID	top(m)	bottom(m)	Rate
1	380280.4	3592230	A	87	42	-400
2	362500.4	3602602	A	90	49.5	-343
3	344085.4	3605777	A	120	92.4	-420
4	339428.7	3587362	A	107	106	-380

Table 3: input parameter

parameter	No. input	parameter	No. input
rainfall	161 mm	Specific yield (Sy)	0.12
groundwater recharge	43.15mm/year	initial head	50
Specific storage Ss	1.2×10^{-4} (1/m)	thickness	155

3.6 Model calibration

The comparison between measured and simulated levels for the aquifer is shown in Figure 7. The model layer and the calculated hydraulic heads were estimated during the Modflow simulation to simulate the layer's flow lines. During calibration, horizontal and vertical hydraulic conductivities were adjusted in sequential model runs to match the simulated heads and measured heads. Steady-state calibration for the flow model was achieved by comparing the hydraulic heads obtained from available groundwater level contour maps. Model results were used during the calibration phase to regress between the calculated data and those observed in groundwater monitoring wells. Based on these results, the estimation (SEE) standard error was 0.067 m. A root mean squared (RMS) value of 0.263 m was achieved during calibration. The normalized RMS for the model was 69.595 %, and the correlation coefficient was 0.391.
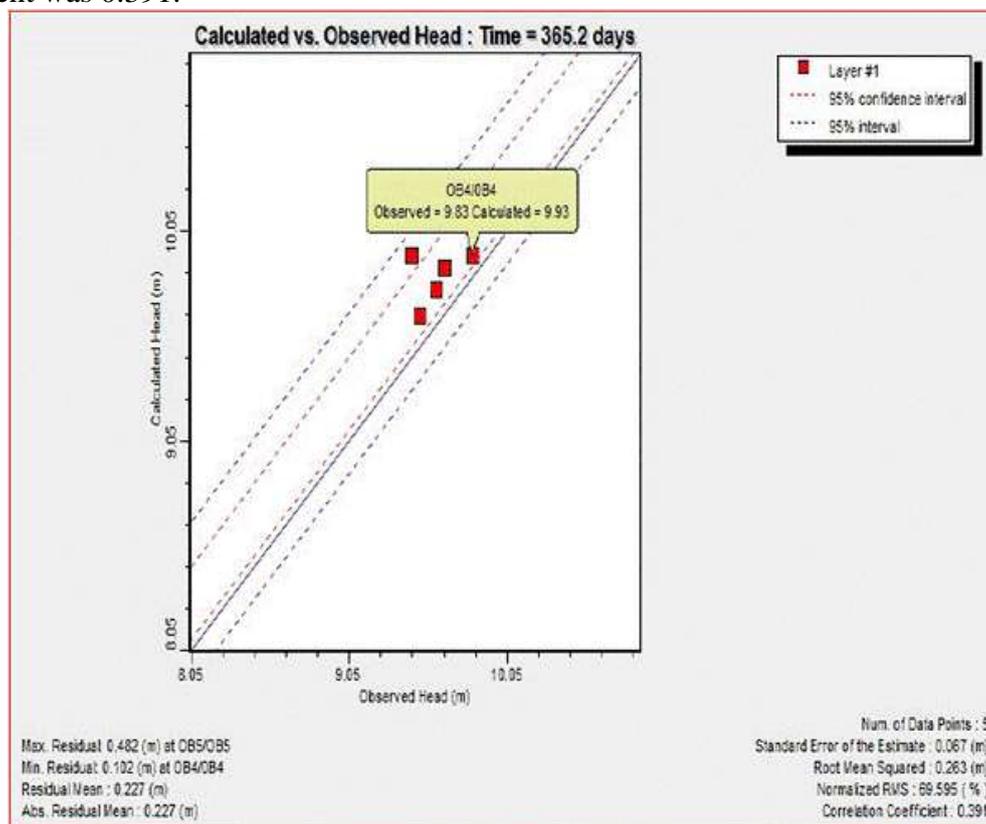
Figure 7: Comparison between the observed and calculated groundwater levels

The simulation of the groundwater head in the area shows that it increases in the middle of the study area and decreases towards the east from 205m to 23m above sea level. It also decreases towards the west but at a lower rate due to the presence of observation and pumping wells. The heads map looks good; it seems they are two head constant along both sides of the map with two flow directions East and Northeast. The contour lines in the central part of the region vary, indicating an increase in conductivity due to the presence of several channels and openings formed as a result of dissolution during the formation of groundwater-bearing rocks, depressions, and lakes, and the contour lines in the eastern and part of the region converge. Groundwater recharge places near the folds' rocky aquifers are located west of the region, Figure (8).
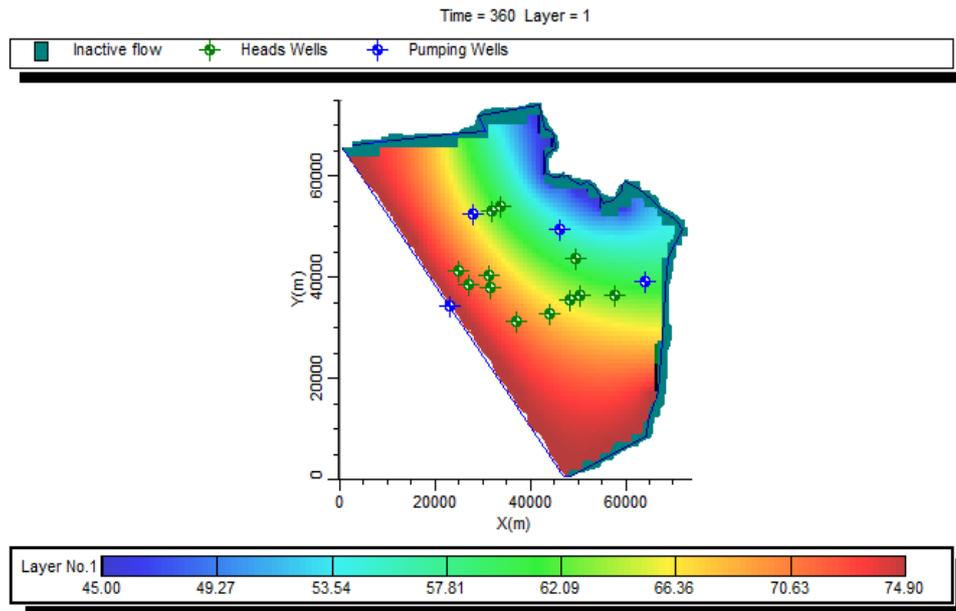
(a)
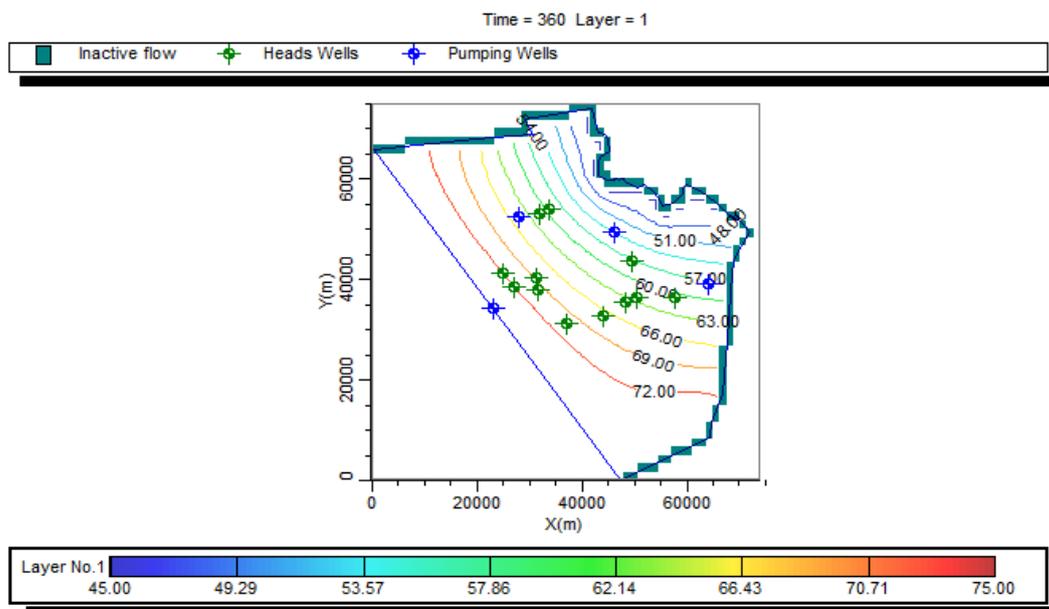
(b)

Figure 8: Groundwater head equipotential contour line in the study area (a), Groundwater Flow direction (b), contour interval.

The contour lines in the central part of the region varied, indicating an increase in conductivity due to the presence of several channels and openings formed as a result of dissolution during the formation of groundwater-bearing rocks, depressions, and lakes, and the contour lines in the eastern and part of the region converge. Groundwater recharge places near the folds' rocky aquifers are located west of the region, Figure 9.

MODFLOW does not display a head value in the unsaturated cell since it only simulates saturated GW flow in the basic model; as a result, the cell gets dehydrated. The water level (stage) tables indicated that the Far East had the highest maximum value of 145m above sea level (m.a.s.l.), and the Far Northeast had the lowest minimum value of 124 m.a.s.l. Constant head borders specified these values at the model's western and eastern bounds. There were no dormant cells or zones included, Figure 10. The GW contour map for the upper Dammam aquifer illustrates that as GW reaches the fault zone, it changes direction somewhat.
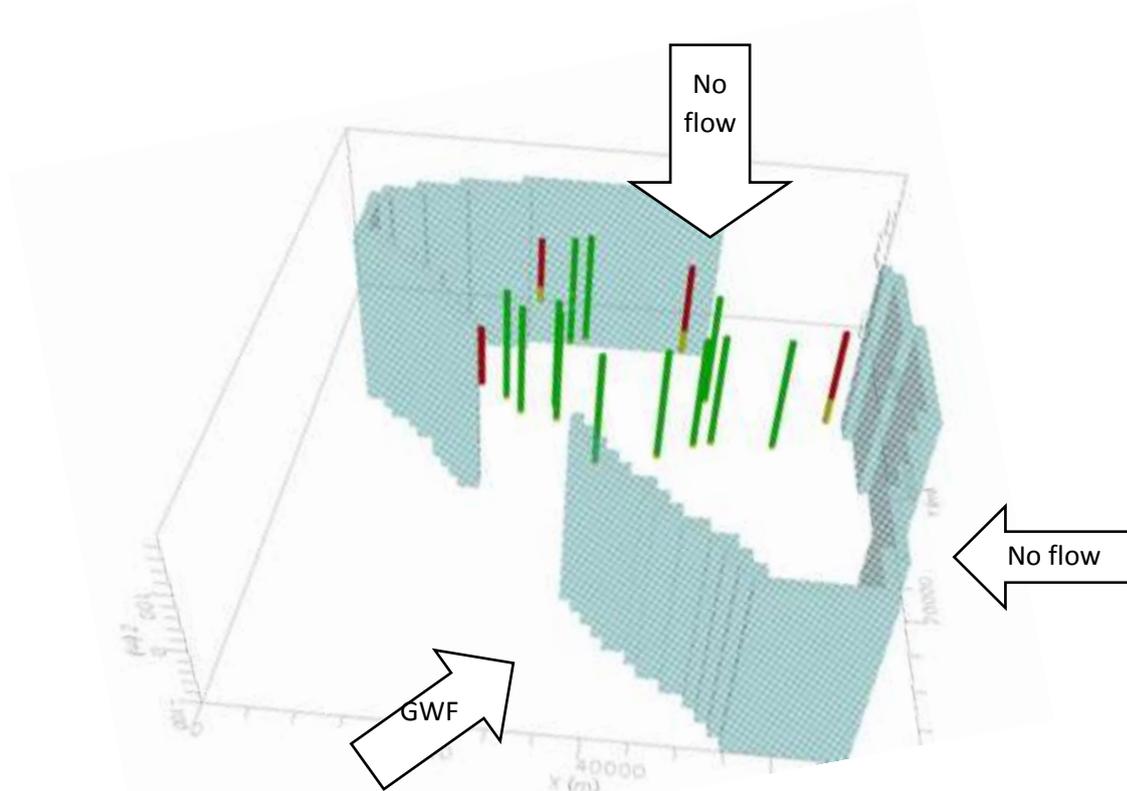
Figure 9: Observation and irrigation well and water table modeling

4. Conclusion

The flow direction was determined using the Karbala steady-state flow model. The aquifer was modeled as a single layer with a constant thickness of 155m in an unconfined environment. The model shows good agreement between observed and calculated water levels, suggesting that research must be conducted to determine the optimum distance between wells to establish water balance and avoid drought. The simulation's findings demonstrated the relevance of artificial recharge in boosting water levels and avoiding constrained aquifer deterioration in quantity and quality. A flow-transport model can simulate flow and solute movement in the study area.

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