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Original Article

Numerical Modeling of Groundwater Aquifer in Debagah Basin - North of Iraq

Hussein Ilaibi Zamil Al-Sudani

Environmental Research Center, University of Technology- Iraq, Baghdad. Iraq.

Corresponding Author : dr.hussein_alsudani@yahoo.com

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Abstract - *Numerical modeling has emerged as a crucial tool across various scientific and engineering disciplines, enabling the simulation and prediction of complex systems. It is a key tool for managing groundwater resources and enables researchers to examine the interactions resulting from various factors, such as recharge and extraction, which can help in developing an optimal plan for utilizing these resources in hydrogeological basins. The numerical model created for the confined aquifer in the central and southern parts of the Debagah basin in northern Iraq showed a decrease in groundwater levels between 13 and 18 meters, mainly in the central-western area of the modeled part of the studied area, after operating the model for five years in the first phase. In the second phase, 25 new wells with a daily discharge of 690 m^3 were added for the same period. The decline observed from the model relates to the pressure within the confined aquifer, not a reduction in the aquifer's thickness, since the piezometric groundwater level before and after the simulation was higher than the aquifer level in all wells. This indicates that the confined aquifer remained fully saturated with water but experienced a decrease in hydraulic pressure. This pressure reduction could be mitigated if the natural recharge rate of the confined aquifer layers increases, suggesting the potential for sustainable groundwater exploitation across the entire modeled area.*

Keywords - *Groundwater, Numerical Modeling, Debagah Basin, North of Iraq.*

1. Introduction

Groundwater modeling is crucial for sustainable groundwater resource management, aiding decisions on development programs concerning both quality and quantity. Groundwater models serve multiple purposes, acting as interpretive tools for analyzing flow patterns and contaminant transport, predictive tools for forecasting future changes, generic tools for evaluating groundwater dynamics and development scenarios, visualizing tools for communication, investigating the impact of well abstraction, understanding contaminant pathways, modeling sea water intrusion, and analyzing management programs' effects on groundwater systems, both quantitatively and qualitatively [1].

The Debagah Basin in northern Iraq depends heavily on this vital resource; the need for reliable groundwater models has become increasingly important in this region. This research presents a case study of a new groundwater modeling approach used in the area, thereby adding to the broader literature on groundwater management. The Debagah Basin has a semi-arid climate and a complex hydrogeological system. The groundwater resources in the Debagah basin are vital for multiple purposes, making accurate numerical modeling of these systems a critical priority. Traditional groundwater modeling methods have often struggled to capture the nuances of the Debagah basin's groundwater dynamics, creating a demand for a more specific approach [2].

Depending on the quality of groundwater in the Debagah basin, which is utilized for many purposes, according to the high ratio of precipitation, it causes an increase in groundwater storage, providing a reliable source for human, livestock, and agricultural use. However, the sustainable development of these vital water resources remains challenging because of increasing agricultural and demographic activities over time. The groundwater is well-defined in terms of chemical compositions and physical properties, indicating good suitability for agricultural and drinking water according to World Health Organization guidelines.

A numerical model is defined as a set of partial differential equations subject to certain assumptions to describe the natural processes in a groundwater aquifer. Numerical models of groundwater movement have been used for many years to solve many hydrogeological problems using subsurface flow equations under various conditions and assumptions. The construction of any mathematical model depends primarily on an understanding of the physical properties of the system under study [3].

As a first step, and to develop a numerical model, understanding the physical behavior of the system and identifying cause-and-effect relationships is a crucial process. The conceptual model will be formulated, which will lead to describing the system's behavior. The second step will be transforming this physical behavior into mathematical equations. This involves making certain assumptions and creating appropriate equations to build the numerical model. The groundwater model with respect to its movement includes a partial differential equation with specific boundary and initial conditions. It is very important to identify the initial conditions that express the mass balance and describe the continuous variables within the study area. The last step of creating the numerical model is to solve the differential equation using analytical or numerical methods. Since analytical solutions are sometimes difficult, numerical methods such as finite difference or finite element are often used. These techniques replace continuous variables with variables divided into small, specific, and known parts at chosen locations within grid cells. Essentially, using the numerical method approximates the continuous partial differential equation at all points, transforming it into a set of equations distributed over time and space. To do this, the total time period under study is divided into smaller intervals, resulting in a set of equations for each sub-time period. These equations form a system of algebraic equations that are solved at each time step [4-7].

The Debagah basin covers an area of approximately 1330 square kilometers, with a rectangular shape oriented northwest-southeast. The studied area lies between 43° 26"- 44° 05" longitude and 35° 33"- 36° 10" latitude. Two mountain ranges surrounded the basin: Avanah to the east and Qara Chauq to the west, while Tigris River tributaries surround the basin from the north with the Upper Zab River and from the south with the Lower Zab River, Figure 1 [2].

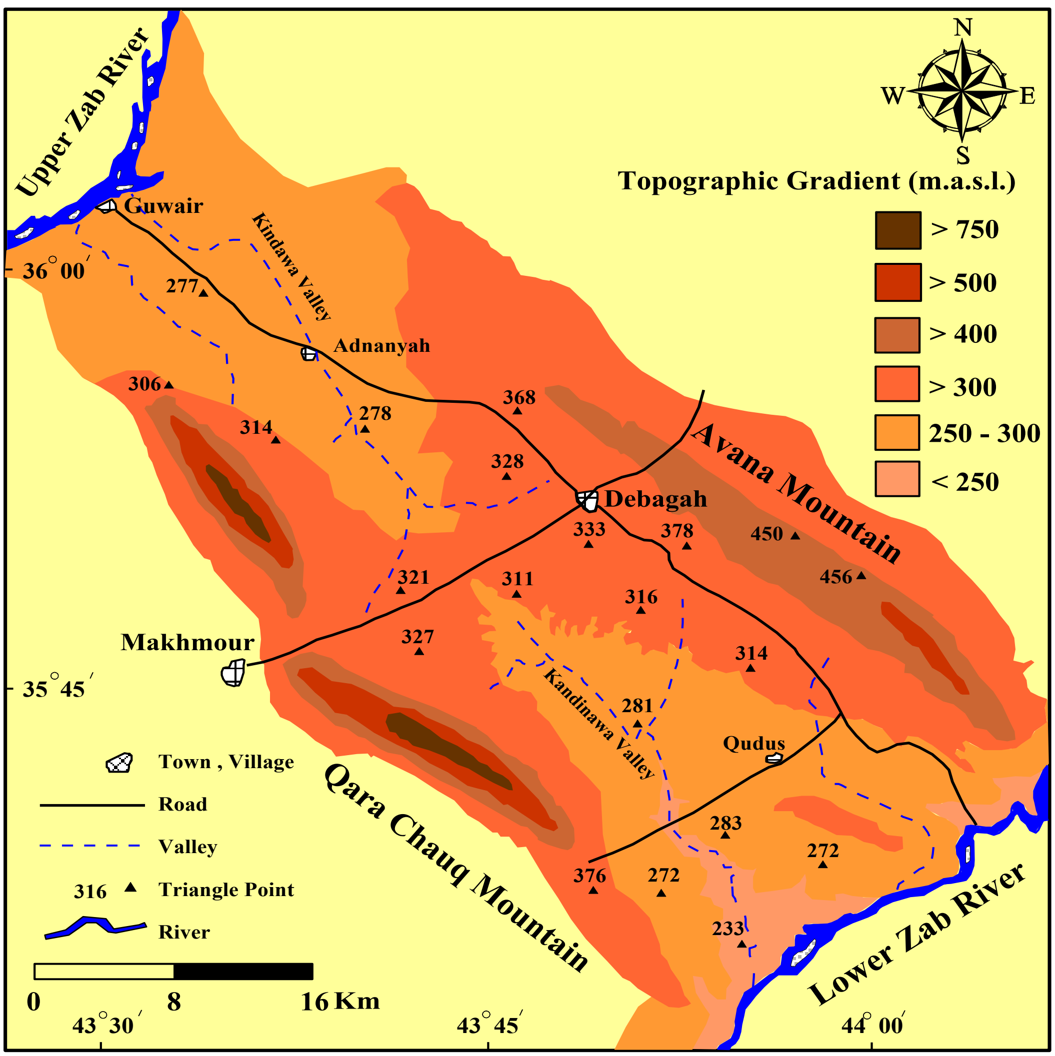
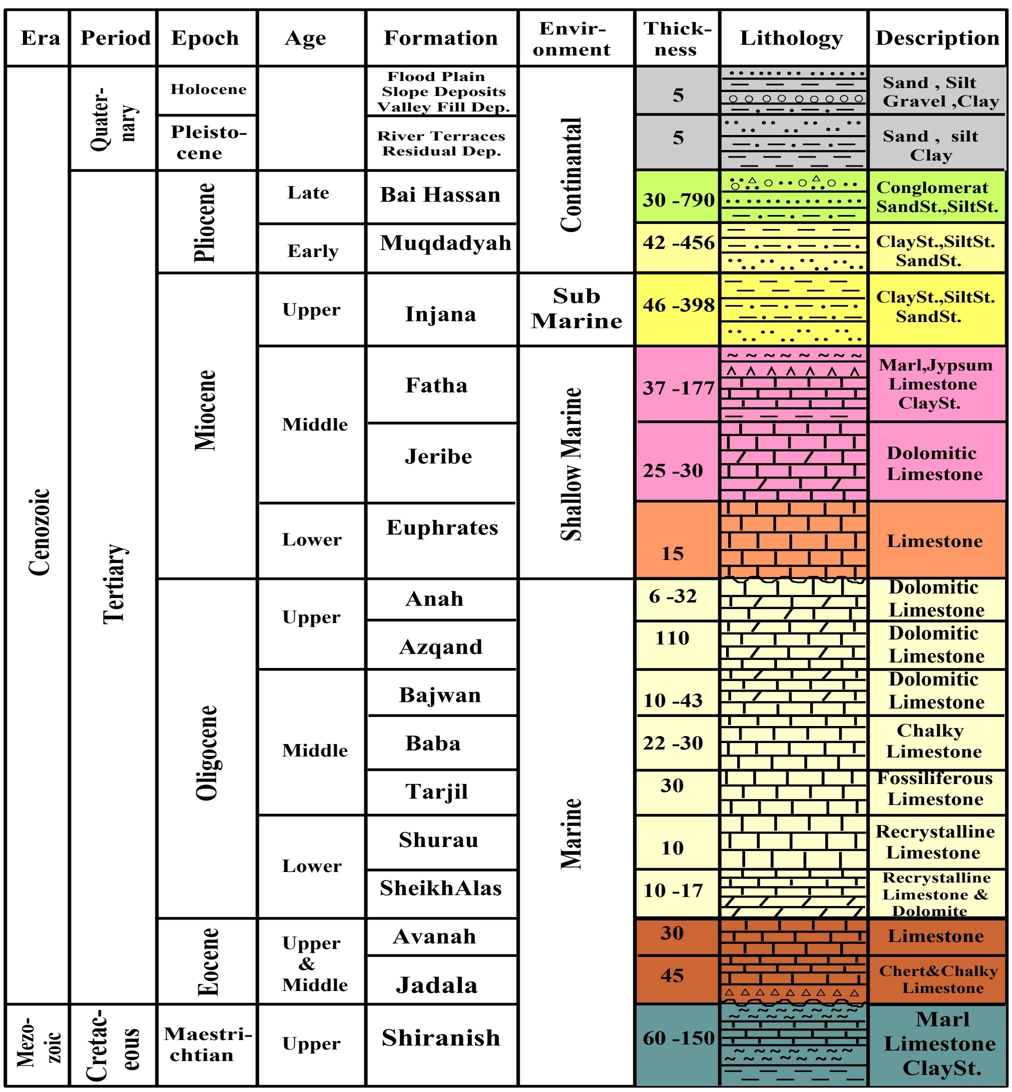


Fig. 1 Location and topographic map of the studied area.

The work plan in the study area included two main parts over two years (2023-2025). The first part was included, collecting all available information and data of the studied area (maps, water wells, stratigraphic columns), in addition to scientific references and the hydrogeological data bank. The second part included field work to survey the drilling water wells to determine their geographical locations, measuring annual fluctuation of stable water levels, and all other geological and hydrological information related to the objective of this research.

The Debagah basin, specifically, and the northern region of Iraq overall have been the focus of numerous geological studies across various disciplines, conducted by multiple organizations. These studies can be divided into two categories:

- The first category was the study of geological and stratigraphic aspects. These studies can be summarized by: The Oligocene – Miocene Stratigraphy of Northern Iraq, The Stratigraphy of the main Limestone of the Kirkuk, Bai Hassan, Qara Chaugh Dagh Structures, Geology of the Southern Area of Kirkuk Liwa, A structural geological study of the Qara Chauq folds [8], Morphotectonics of the Tigris River and its tributaries within the fold, and Geomorphology of the low folded zone.
- The second category was the assessment of surface and groundwater, as well as hydrogeological and hydrochemical properties of aquifers in the area. These studies can be summarized by: Water supply in Iraq, Ground Water Resources of Iraq, A hydrological study of the upper Zab River Basin in Iraq [9], Hydrogeological and Hydrochemical Properties of Groundwater in Jolak Wadi Basin [10], Hydrogeological investigations, Debagah and Makhmur regions [3], and Hyrogeological system of Debagah basin in North of Iraq [2].



2. Description of the Studied Area

The Debagah basin features contrasting topography, with high mountains on the east and west sides and a relatively flat plain in the middle. The basin is asymmetrical, situated between two long, parallel mountain ranges with different stratigraphic inclinations—specifically, the rock layers along the western range (Qara Chauq Mountains) are more inclined than those along the eastern range (Avana Mountains) [8]. The Debagah basin is divided into two parts based on slope, with the central lands being higher than the northern and southern areas. Consequently, several seasonal valleys form, flowing periodically from the surrounding mountains into the middle of the basin. These valleys converge at the center and then flow southward into the Kandinawa stream, which feeds the Lower Zab River. To the north, these valleys drain into the Kindawa stream, which eventually joins the Upper Zab River [2]. Geologically, the region is made up of sedimentary rocks dating from the Cretaceous to the Pliocene, along with various types of Quaternary deposits. Structurally, most of the area falls within the Foothill and High Folded Zones, with a small section in the Mesopotamian Zone. The Foothill Zone contains two subzones: Hemrin-Makhul and Cham-Chamal-Butmah, while the Mesopotamian Zone is represented by the Tigris Subzone [11].

The exposed formations in the area span a wide stratigraphic range from Cretaceous to Quaternary deposits. These formations are listed in the following table [2,8,11,12].

3. Materials and Methods

The materials used in this study were:

1. Topographic and geological maps at a scale of 1:250000.
2. Fifty-five- five drilling wells and their stratigraphic sheets, and the hydrogeological data bank.
3. Aquifer Simulation Model (ASM) [13].
4. Mathematical programs (Surfer and Excel) to analyze the data and information obtained and draw all types of maps.

To build up the numerical model as the study's objective, the hydrogeological information was obtained from previous studies. This information indicated that there are two types of aquifers, the unconfined and confined one. Other information was utilized to determine the characteristics of the confined aquifer in the basin, as well as all information regarding water surplus, groundwater recharge, discharge, and any other information, which can facilitate building the numerical model [2].

The numerical model of the central and southern parts of the Debagah basin was designed in the form of a grid consisting of (18) rows and (15) columns, i.e., (270) regular cells, each with an area of (4) km^2. The subsurface flow is the main source of recharge for the confined aquifer in the central parts of the area; these waters are infiltrated from rainfall and help maintain its groundwater storage. The total amount of this water in the aquifer represents the primary inputs to the hydrogeological system. The twenty-six wells discharge water, and the subsurface flow toward the south of the basin is the main output of the system. The designed model was run in two stages. In the first stage, the quantity of groundwater entering the aquifer was determined under steady flow conditions. In the second stage, the model was operated under unsteady flow conditions.

In order to operate the model correctly and obtain accurate results, the model should be calibrated and verified. The calibration process of a numerical model has two main purposes: first, to ensure that the model accurately represents the properties of the physical problem and variables over time and space; second, to verify that all the physical inputs to the model, which reflect the hydrogeological system inputs, are consistent and balanced with the outputs. To accomplish this, the model is operated under either steady-state or unsteady-state flow conditions for a relatively long period until the difference in groundwater levels between successive periods becomes negligible. This process involves adjusting input parameters such as hydraulic conductivity and storage coefficient until a reasonable match is achieved between field measurements and model-generated data, recognizing that these inputs are not precisely known and may vary within certain ranges [1]. The next step towards validating the model for predicting future groundwater levels and their spatial variations is model verification. This entails running the model under unsteady flow conditions over a specified timeframe and comparing the outputs, such as groundwater levels or declines, with field data from wells distributed across the basin. Additional modifications to model inputs may be necessary, which can be identified through sensitivity analysis [14]. Sensitivity testing aims to identify which hydrological or hydrogeological factors directly impact the groundwater system. This involves observing how changes in specific inputs affect the difference between calculated and observed field levels. Typically, one input is varied by a certain percentage while others remain constant, and the effects are analyzed [3]. The ASM program adjusts the transmissivity values, as this parameter is the only variable input in the model. The adjustment occurs through automatic calibration, where the program is provided with upper and lower limits for transmissivity in each grid cell. It then iterates through multiple steps, which may take considerable time, to find appropriate and consistent groundwater levels relative to the field data.

4. Results and Discussion

4.1. Confined Aquifer Characterization

The hydrogeological system of groundwater in the Debagah basin was determined by analyzing data from fifty-five drilled wells in the confined aquifer. The Muqdadiya and

Bai Hassan formations, which formed the confined aquifer, are considered the most significant groundwater sources in the study area because of their extensive, continuous extension and the importance of their saturated thickness. Therefore, these two geological formations are regarded as a single hydrogeological unit where groundwater can be exploited [2,15]. Table 1 shows the hydrogeological characteristics of the confined aquifer, while Figure 2 shows the flow net map of the confined aquifer in the Debagah basin.

Table 1. Hydrogeological characteristics of the confined aquifer after [2]

Parameters	Elevation (m.a.s.l.)	Well Depth (m.)	Aquifer Depth (m.)	Aquifer Thickness (m.)	S.W.L. (m.)	Piezometric Level (m.a.s.l.)	Discharge (m^3/day)	Specific Capacity (m^2/day)
Number of values	55	55	55	55	55	55	55	55
Minimum	225	90	30	19	9	215.4	1.78	129.6
Maximum	380	240	166	105	75.6	350.4	388.8	1296
Mean	288.28	159	75.07	46.9	32.76	272.38	102.17	652.75

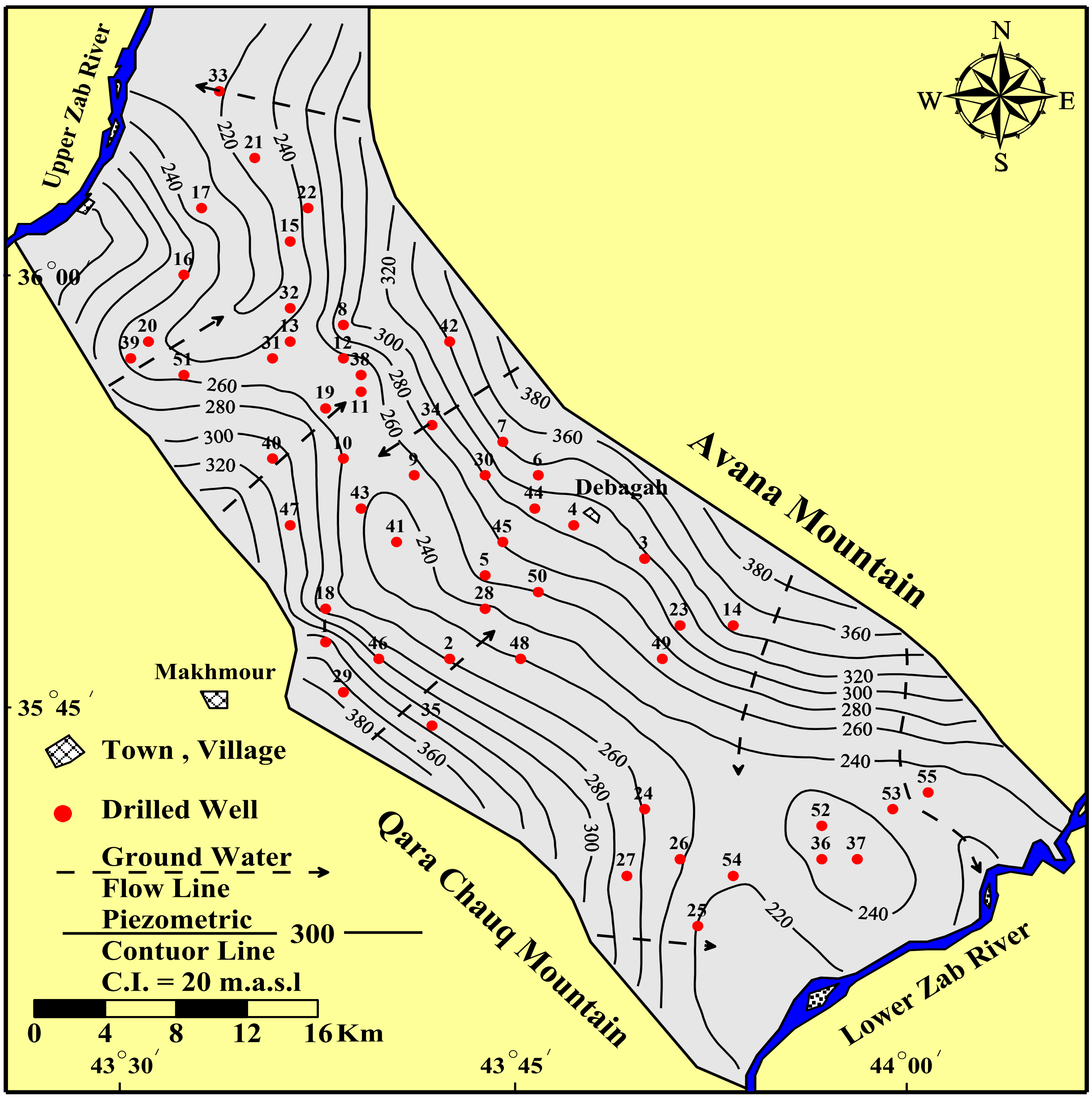


Fig. 2 Flow net map of confined aquifer in Debagah basin

4.2. Numerical Model Application

4.2.1. Steady-State Flow Operation

Operation of steady-state flow is the first step in understanding the behavior of a system under natural conditions, and then use the results of this state as initial inputs for the unsteady-state flow, which is the basis for operating the numerical model in long-term behavior of the aquifer, especially in cases where previous groundwater levels observations are available, in addition to its impact by various natural and artificial factors, such as pumping or injection operations, etc. [16]. The external boundaries of the numerical model, as shown in Figure 3, were considered to have a constant level, while the remaining grid cells were considered to have a variable level.

After establishing all input data for the numerical model, the model was run under steady flow conditions until the measured groundwater levels matched the calculated levels from the model as closely as possible. This process often requires adjusting values such as transmissivity or hydraulic conductivity, since the numerical model aims to stabilize the water flow entering from the model boundaries, which represent the ideal recharge of the confined aquifer.

Table 2 shows the comparison between measured and calculated levels for selected cells of the model, while Figure 4 displays the map of groundwater levels from the calibrated model. It is observed that there is a suitable pattern between the measured levels shown in Figure 2 and the modeled levels, indicating the same direction of groundwater movement in the central and southern parts of the basin.

Table 2. Measured groundwater levels and calculated levels in selected cells of the model

Well No.	Cell i	Cell j	Measured Head (m.a.s.l.)	Calculated Head (m.a.s.l.)	Well No.	Cell i	Cell j	Measured Head (m.a.s.l.)	Calculated Head (m.a.s.l.)
1	2	2	350.4	350.27	26	5	13	242	242.27
2	5	4	257.8	257.18	27	4	12	267	268.4
3	11	5	317.2	317.98	28	6	3	239	242.34
5	7	2	265.3	264.7	36	8	15	240	235.8
14	11	5	347	347.19	52	9	14	250	246
23	9	7	307	305.19	53	11	15	234	238.25
24	6	11	256.6	260	55	12	15	234	237.52

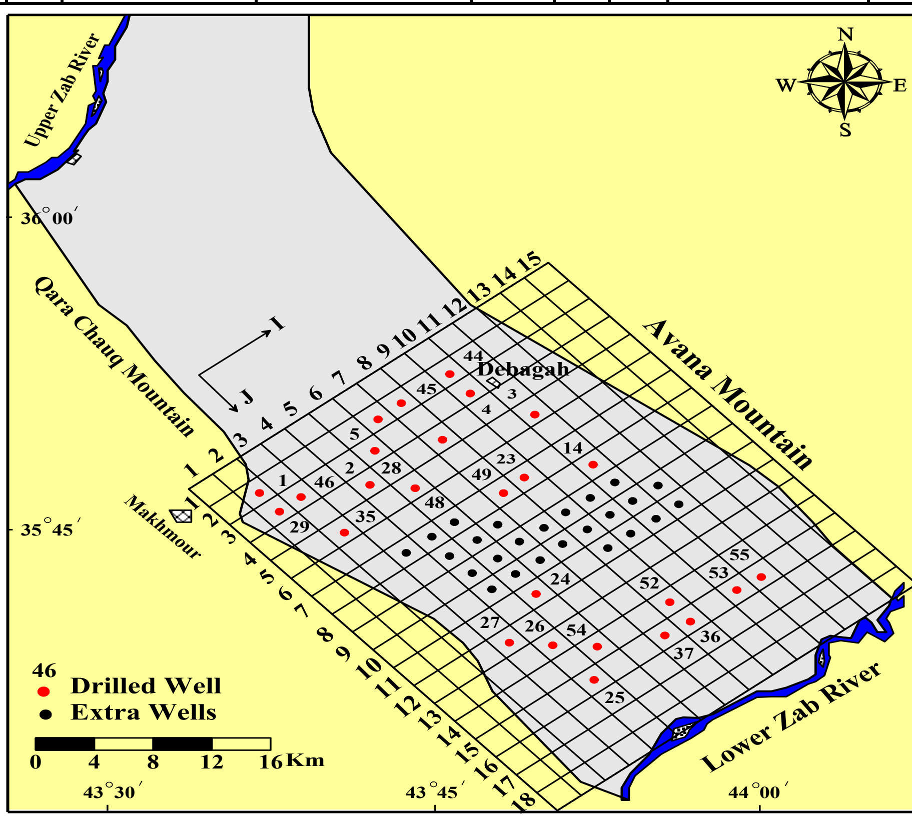


Fig. 3 Dimensions of the numerical model designed for the Debagah basin

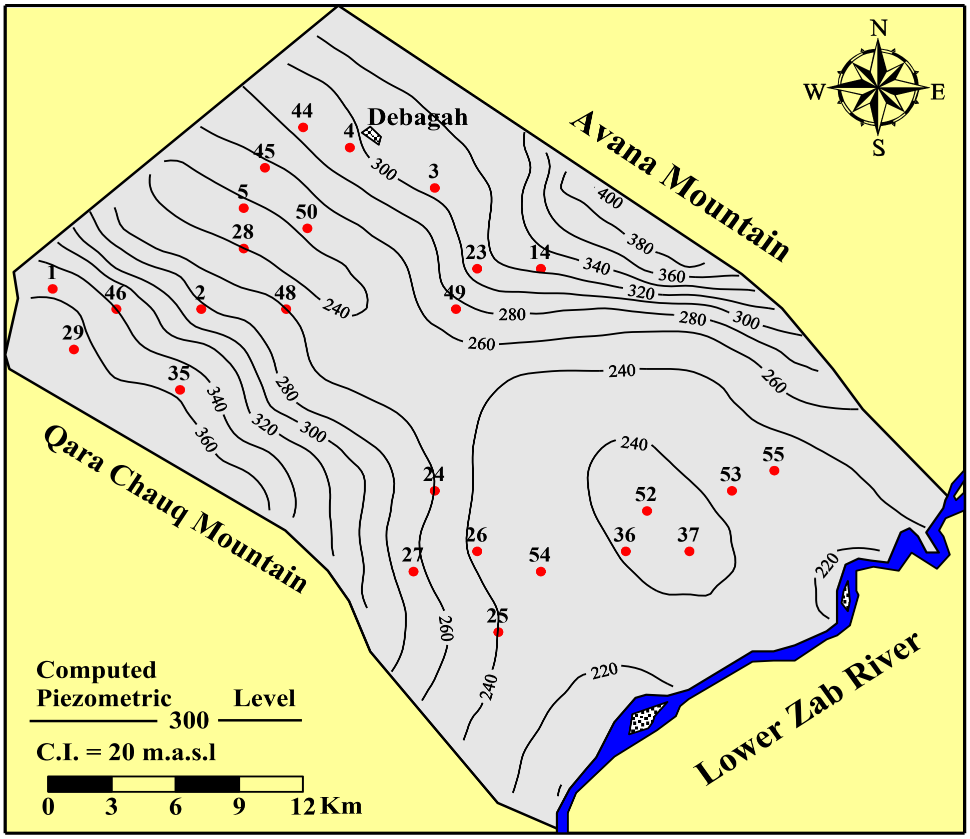


Fig. 4 Groundwater levels map from the calibrated model

4.2.2. Unsteady-State Flow Operation

The groundwater level values from the calibrated model were used as initial inputs for steady flow to represent unsteady flow. The twenty-six wells distributed within the model area operated with pumping rates ranging from 194.4 to 864 m³/day. The eastern and western boundaries of the area, represented by the Avana and Qara Chauq mountains, were chosen as no-flow borders because they represent recharge areas for the confined aquifer. The northern and southern boundaries are also assumed as no-flow borders, since groundwater flow is parallel to these borders. Other cells in the model were assigned variable groundwater levels. The annual recharge rate is assumed to be 4.4 mm, based on water balance calculations by the author and previous studies [2].

To develop the area in a way that enables predicting changes in the groundwater level, considering the current or future groundwater exploiting plan by increasing the number of wells that can be drilled and their effects on the basin's hydrogeological system, it was necessary to compare the groundwater levels obtained from the numerical model under unsteady flow conditions with observed measurements of groundwater levels in the field study. This helps to represent the system's behavior over the long term and to assess the impact of natural and artificial factors. This process is called verification of the designed model.

The numerical model was operated under unsteady flow conditions depending on the number (23, 36), where their groundwater levels were monthly measured during (2024-2025). The discharge rates of the twenty-six wells, groundwater levels obtained under steady flow conditions, and the changed boundary conditions were considered the main inputs for the new stage of model operation.

The operation process included changes in some values and parameters entered into the model until reaching the groundwater levels similarity between the measured and computed levels, as shown in Table 3. It is now possible to predict the changes in groundwater levels and the behavior of the confined aquifer according to a specific exploitation plan in a long-term perspective.

The numerical model was run for five years with twenty-six wells distributed in the area, as mentioned previously. This process will give a perspective of the impact on aquifer pressure and the groundwater levels drop according to the moderate discharge of wells and a low natural groundwater recharge rate. The numerical model was then run for five years again, with the same recharge rate, but with an additional twenty-five extra wells of daily discharge rate of (690) cubic meters. The locations of these new wells and the additional wells are shown in Figure 3.

Figure 5A displays a map of the groundwater level decline in the first case. The results indicate a decline in groundwater levels in the central-western part of the modeled area, reaching 13 meters, while in other parts of the area, the decline ranges between 1 meter and 3 meters. The decline in observed groundwater levels in the central-western part is caused by low transmissivity due to aquifer lithological variability [17].

Running the model in the second case, shown in Figure 5B, with the additional twenty-five new wells in the center of the modeled area, caused groundwater levels to decline by 18 meters within the central-western part of the area due to the effects of the discharges of the additional wells and low transmissivity mentioned in the first case of the model running. The entire model area showed consistent levels of decline in the groundwater levels from both directions, from the southwards and northwards towards the central area. The declination ranged between 2 and 8 meters. The model results showed that the groundwater level declination is related to the pressure level of the confined aquifer and not a decline within the saturated thickness of the aquifer, as the piezometric groundwater level indicated before and after running the model was at a higher level than the aquifer depth and for all wells, and this means that the confined aquifer remained completely saturated and suffered a decrease in hydraulic pressure at levels (13) and (18) m.

Table 3. Comparison of the calculated groundwater levels with measured levels in (2024-2025)

Month	Well No. 23			Well No. 36		
	Static water Level m.	Measured Head m.a. s. l.	Calculated Head m.a. s. l.	Static water Level m.	Measured Head m.a. s. l.	Calculated Head m.a. s. l.
Oct.	64.91	306.09	307.7	27.73	238.27	238.38
Nov.	64.91	306.09	307.03	27.75	238.25	238.84
Dec.	64.9	306.1	307.08	27.67	238.33	238.4
Jan.	64.9	306.1	307.27	27.56	238.44	238.52
Feb.	64.9	306.1	307.25	27.52	238.48	238.56
Mar.	64.92	306.08	307.06	27.5	238.5	238.64
Apr.	64.91	306.1	307.1	27.4	238.6	238.6
May	64.91	306.1	306.8	27.53	238.47	238.64
Jun.	64.91	306.09	306.92	27.57	238.43	238.49
Jul.	64.91	306.09	306.78	27.65	238.35	238.47
Aug.	64.91	306.09	306.88	27.7	238.3	238.43
Sep.	64.9	306.1	306.58	27.78	238.22	238.46

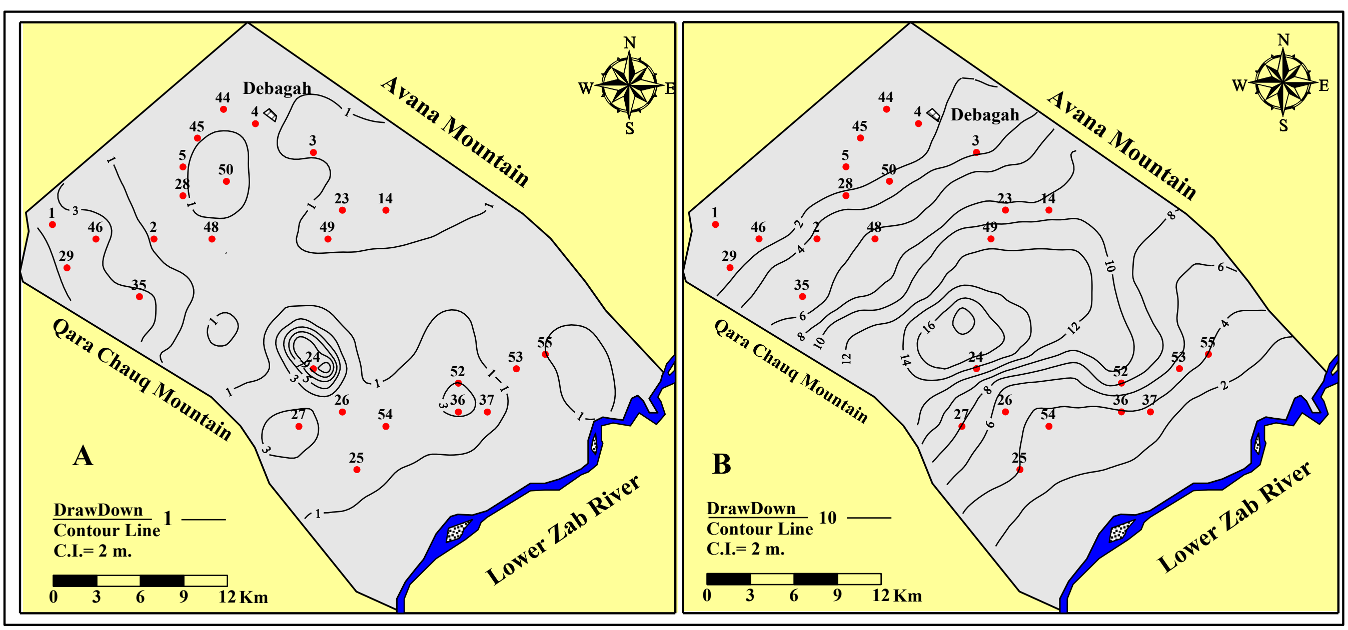


Fig. 5 Groundwater levels map computed from the model (A: first case, B: second case)

5. Conclusion

- Based on the low level of natural groundwater recharge adopted in the operation of the numerical model, it can be said that the general decline in groundwater levels relates to the basic groundwater storage in the aquifer, without any noticeable effect of natural recharge activities .
- It is possible to depends on the basic groundwater storage to exploit groundwater from the aquifer, even in the absence of natural recharge for a period of five years, without drilling any additional wells especially in the central-western part of the modeled area, which recorded a decrease of (13) meters as a maximum declination of saturated thickness of (25) meters, while this thickness remains saturated with groundwater. This will allow the central-eastern part in particular, to be saturated with groundwater, and a suitable exploitation of groundwater by drilling wells with a depth not exceeding (100) meters, with a saturated thickness ranging between (25) and (50) meters, and a decrease in their hydraulic pressure level not exceeding (5) meters.
- The addition of new wells to the modeled area must take into consideration the distances between wells that can be drilled to prevent overlapping of well depression levels, which would affect the pressure of the confined aquifer and the wells' ability to produce water. The proposed distance between wells must not be less than 500 meters.

References

[1] G.T. Patle et al., “Modelling of Groundwater Recharge Potential from Irrigated Paddy Field under Changing Climate,” *Paddy and Water Environment*, vol. 15, pp. 413–423, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[2] Hussein Al-Sudani, “*Hyrogeological System of Debagah Basin in North of Iraq*,” Ph.D. Thesis, University of Baghdad, College of Sciences, 2003. [Google Scholar] [Publisher Link]

[3] Vijendra Kumar et al., “Comprehensive Overview of Flood Modeling Approaches: A Review of Recent Advances,” *Hydrology,* vol. 10, no. 7, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[4] Jiaqi Tang, Jitang Fan, and Shaohua Chen, “A Numerical Model for Calculating the Impact-induced Depression,” *International Journal of Impact Engineering*, vol. 183, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[5] Dmitry Sharapov, “Water Circulation to Improve the Quality of Port Ice Management,” *International Journal for Quality Research*, vol. 18, no. 2, pp. 603–612, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[6] Ashneel Sharan et al., “Management of Saltwater Intrusion Using 3D Numerical Modelling: A First for Pacific Island Country of Vanuatu,” *Environmental Monitoring and Assessment*, vol. 196, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[7] W. Kinzelbach, and R. Rausch, “Aquifer Simulation Model,” *International Groundwater Modelling Center*, Netherlands, 1995. [Google Scholar]

[8] R.C. Van Bellen, “The Stratigraphy of the Main Limestone of the Kirkuk, Bai Hassan, Qara Chaugh Dagh Structures,” *Journal Institute Petroleum Journal,* vol. 42, no. 393, pp. 233-263, 1956. [Google Scholar] [Publisher Link]

[9] Manal Shaker Ali Al-Kubaisi, “*Morphotectonics of the Tigris River and its tributaries within the fold zone in Iraq*,” PhD. Thesis, University of Baghdad - College of Science, 2000. [Google Scholar]

[10] Sabah Y. Yacoub, Arsalan A. Othman, and Talal H. Kadhim, “Geomorphology of the Low Folded Zone,” *Iraqi Bulletin of Geological Mining*, no. 5, 2012. [Google Scholar] [Publisher Link]

[11] Tibor Buday, and Jaroslav Tyráček, *The Regional Geology of Iraq: Tectonism, Magmatism and Metamorphism*, State Organization for Minerals, Directorate General for Geological Survey and Mineral Investigations, vol. 2, 1980. [Publisher Link]

[12] V.K. Sissakian, “The Geology of Kirkuk Quadrangle Sheet NI-38-2 (GM 9) Scale 1:250 000,” *International Report, Geosurv-Iraq*, 1992. [Google Scholar]

[13] Wolfgang Kinzelbach, Randolf Rausch, and Wen-Hsing Chiang, *Aquifer Simulation Model for Windows: Ground Water Flow Transport Modeling*, An Integrated Program, 1998. [Google Scholar] [Publisher Link]

[14] Mary P. Anderson, William W. Woessner, Randall J. Hunt, *Applied Groundwater Modeling: Simulation of Flow and Advective Transport*, Elsevier, 2015. [Google Scholar] [Publisher Link]

[15] Hussein I. Al-Sudani, “Hydraulic Parameters of Groundwater Aquifers in Khan-Al-Baghdadi Area,” *Engineering and Technology Journal,* vol. 36, no. 2, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[16] Patrick A. Domemico, and Franklin W. Schwartz, *Physical and Chemical Hydrogeology*, John Wiely and Sons. Inc., 1998. [Google Scholar] [Publisher Link]

[17] Hussein Ilaibi Zamil Al-Sudani, “Hydrogeological Conditions and Groundwater Geochemistry of Badra - Zurbatia Area in Wasit Governorate - East of Iraq,” *International Journal of Recent Engineering Science*, vol. 12, no. 3, pp. 1-9, 2025. [CrossRef] [Publisher Link]