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Developing three-dimensional groundwater flow modeling for the Erbil Basin using Groundwater Modeling System (GMS)

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Abstract: This study presents the development of a comprehensive three-dimensional groundwater flow model for the Erbil Basin utilizing the Groundwater Modeling System (GMS). The Erbil Basin, situated in the Kurdistan Region of Iraq, is a vital water resource area facing increasing water demands and environmental challenges. The three-dimensional nature of the groundwater flow system is crucial for accurately understanding and managing water resources in the basin. The modeling process involved data collection, geological and hydrogeological characterization, conceptual model development, and numerical simulation using GMS software MODFLOW 2000 package. Various parameters such as hydraulic conductivity, recharge rates, and boundary conditions were integrated into the model to represent the complex hydrogeological conditions of the basin. Model calibration was performed by comparing simulated groundwater levels with observed data from monitoring wells across the basin, using the automatic calibration method of automated Parameter Estimation (PEST). Pilot points were applied to adjust the hydraulic conductivity in the model area spatially. Sensitivity analysis was conducted to assess the influence of key parameters on model predictions and to identify areas of uncertainty. The developed three-dimensional groundwater flow model provides valuable insights into the dynamics of groundwater flow, recharge-discharge mechanisms, and potential impacts of future scenarios such as climate change and water resource management strategies. It serves as a useful tool for decision-makers, water resource managers, and researchers to evaluate different management scenarios and formulate sustainable groundwater management policies for the Erbil Basin. In conclusion, this study demonstrates the effectiveness of using GMS for developing three-dimensional groundwater flow models in complex hydrogeological settings like the Erbil Basin, contributing to improved understanding and management of groundwater resources in the region.

Keywords: Aquifer System; Erbil Basin; Groundwater Management; GMS; MODFLOW

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Introduction

In recent years, numerous studies have highlighted the alarming consequences of inadequate water resources management, particularly evident in the depletion of the aquifer system within the Erbil Basin. The critical needs to address this issue is underscored by the imperative to develop comprehensive strategies for managing both surface and groundwater resources. The intricate interplay between surface and subsurface water systems necessitates a thorough investigation to inform sustainable water resources planning. Recognizing the pivotal role of subsurface models in maintaining the longevity and effective management of water resources, this study focuses on the Erbil basin, aiming to contribute insights that will inform informed decision-making and foster sustainable practices for the benefit of both the environment and the local communities.

Most recent studies have reported that the lack of water resources management causes depletion in aquifer system in Erbil Basin. In addition, to develop both surface and groundwater management, it is necessary to study the interactions between them in order to make decision on sustainable water resources planning. Subsurface models play a major role in maintaining the sustainability and

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management of water resources (Mustafa and Mawlood, 2023). The proposed solutions and strategies lead to address the existing challenges and align with global sustainability goals, highlighting the crucial role of groundwater modeling in shaping informed decision-making for water resource management (Bassi and Kumar, 2012). Due to the importance of groundwater modeling, many researchers have been studying on this issue. Many investigations carried out in regions of Iraq involved the modeling of the groundwater movement using MODFLOW model. However, due to the complexity of Iraqi aquifers, there is a lack in groundwater data in Iraq, leading to shortages in the groundwater management planning (Dizayee, 2014). Nevertheless, several studies are carried out in different regions in Iraq. Some studies utilized GMS program to develop three-dimensional numerical groundwater flow models using the MODFLOW package to estimate both groundwater flow direction and quantity for Sullivan plain in Mosul, Iraq. The literature review presents a comprehensive overview of groundwater studies conducted in various regions of Iraq, focusing on factors such as movement, recharge, and management. In a study by Hussain (2008), groundwater flow within the Sullivan plain was estimated to be approximately 579,655 m^3/d. Subsequently, Hussain applied two numerical models to assess groundwater recharge in Karbala, utilizing GMS software with the MODFLOW package and Quick Basic language for mathematical modeling. The study identified sources of groundwater recharge, including leakage from sanitary systems, septic tanks, and drinking pipe networks ranging from 760.71 m^3/d to 3,256.758 m^3/d. Al-Muqdadi (2012) employed Visual MODFLOW software to model groundwater flow in the western part of Iraq, estimating a recharge of 0.0479 mm/d over 30 years. Additionally, Hussien (2012) investigated groundwater management in Dhabaa area, reporting aquifer velocities between 0.0008 m/d and 0.23 m/d. Ramadhan et al. (2013) studied recharge in Karbala and Najaf, using MODFLOW software, with estimates of 0.0619 mm/d. Al-Mussawy (2013) utilized GMS software version 7.1 to simulate confined aquifer flow in Karbala, yielding a recharge range of 2.74×10^{-9} mm/d to 8.49×10^{-8} mm/d. Seeyan and Merkel (2015) used Visual MODFLOW to model unconfined aquifer systems in Harrir and Mirawa Basins, reporting recharge values of 0.139 mm/d, 0.313 mm/d, and 0.239 mm/d. Karim and Ali (2017) employed a 2D model for simulating groundwater flow in confined aquifer types in Karbala. Khayyun and Mahdi (2020) explored 3D geo-statistics interpolation in GMS for aquifers in Iraq. Zwain and Abed (2023) investigated Al-Ruhbah area in Najaf, simulating groundwater flow using GMS software with a 3D model. Ali and Oleiwi (2015) studied aquifer drawdown in Khanaqin, Iraq, using MODFLOW. Jasim and Jalut (2020) focused on modeling Baquba area's shallow unconfined aquifer, using GMS version 10.0 and MODFLOW-2000, calibrating hydraulic conductivity and recharge rate parameters. Seeyan (2020) simulated groundwater head for Qushtepa Plain within Erbil basin. Finally, Yashooa and Mawlood (2023a; 2023b) analyzed groundwater flow and simulated contaminant transport in an area of Erbil City. The wealth of information from these studies contributes significantly to our understanding of groundwater dynamics in diverse Iraqi regions. The utilization of groundwater modeling has become indispensable for understanding the complex dynamics of groundwater flow within aquifers, particularly in regions facing water resource management challenges like the Erbil basin. Studies consistently reveal the depletion of aquifer systems due to inadequate water resource management practices. To address this concern and concurrently manage both surface and groundwater effectively, it is imperative to investigate the complex interactions between these systems. Groundwater modeling software, such as the Groundwater Modeling System (GMS), has emerged as a robust solution for hydrogeologists and engineers to develop numerical models, allowing for the prediction of water movement, contaminants, and other subsurface phenomena.

This study contributes to the existing knowledge by developing a groundwater flow model for the Erbil basin. Previous research has primarily focused on specific aspects of the basin's hydrology, leaving a notable gap in comprehensive 3D groundwater flow modeling. Addressing this gap is crucial for gaining a comprehensive understanding of the basin's hydrological processes and ensuring effective management of its water resources. Consequently, conducting a thorough 3D groundwater flow modeling study is imperative to provide invaluable insights for sustainable water resource management in the Erbil Basin.

The main goal is to create a comprehensive groundwater flow model for the Erbil Basin aiming to understand the intricate behavior of the aquifer system within the region. The model seeks to simulate groundwater movement and distribution to provide a detailed representation of the hydrological processes. Key objectives include contributing to water resource planning and management in the Erbil Basin, assessing groundwater availability and sustainability, and informing decisions regarding water usage and allocation.

1 Materials and methods

1.1 Location of the study area

The Erbil Basin, situated in the northern part of Iraq, is delineated by the Greater Zab and Lesser Zab Rivers to the northwest and southeast, respectively. This basin is further sub divided into three main sub-basins, namely KAPRAN, CENTRAL, and BASHTHEPA. The collective area of these sub-basins covers approximately 3,200 km² (Mustafa and Mawlood, 2023; Mawlood, 2019). The geographic coordinates place the region between longitude of 44.00° E and latitude of 36.19° N, with an elevation of around 420 m above sea level. The climate in this area is characterized as arid and semi-arid, posing challenges for water availability and resource management. A visual representation of the basin's location can be found in Fig. 1.

1.2 Hydrogeological conditions of Erbil Basin

The geographical boundaries of the Erbil Basin are delineated by distinct features, with the Greater Zab River marking its northwestern extent. To the northeast, the basin is defined by the commencement of the High Folded Zone, notably evident in elevated regions such as the Al Mewan Anticline and Pirmam Anticline, where the Pila Spi Formation outcrops. In the southeast, the Lesser Zab River forms the basin's boundary, while the southwestern extent is characterized by the Kirkuk Anticline (Shekhmamundy and Surdashy, 2022). Groundwater dynamics within the Erbil Basin typically involve a flow from the upstream mountainous areas towards the Greater Zab River, identified as a discharge area in the basin (Mohammed et al. 2013). The Aquifer System in the Erbil Basin receives an estimated average of precipitation per year, highlighting the significance of understanding the hydrological processes in this region. More details show in (Fig. 2).

The groundwater flow direction within the study area generally directs from northeast towards south west of the area (Mustafa and Mawlood, 2023), see Fig. 3 .

2 Data collection and modeling applications

2.1 Principle of groundwater flow modeling

A groundwater model serves as a powerful tool for quantitatively representing groundwater heads within a simplified depiction of the intricate hydrogeologic conditions. This modeling approach is instrumental in understanding and predicting the behavior of groundwater systems. Groundwater models can broadly be categorized into two types: Physical and mathematical models (Anderson et al.

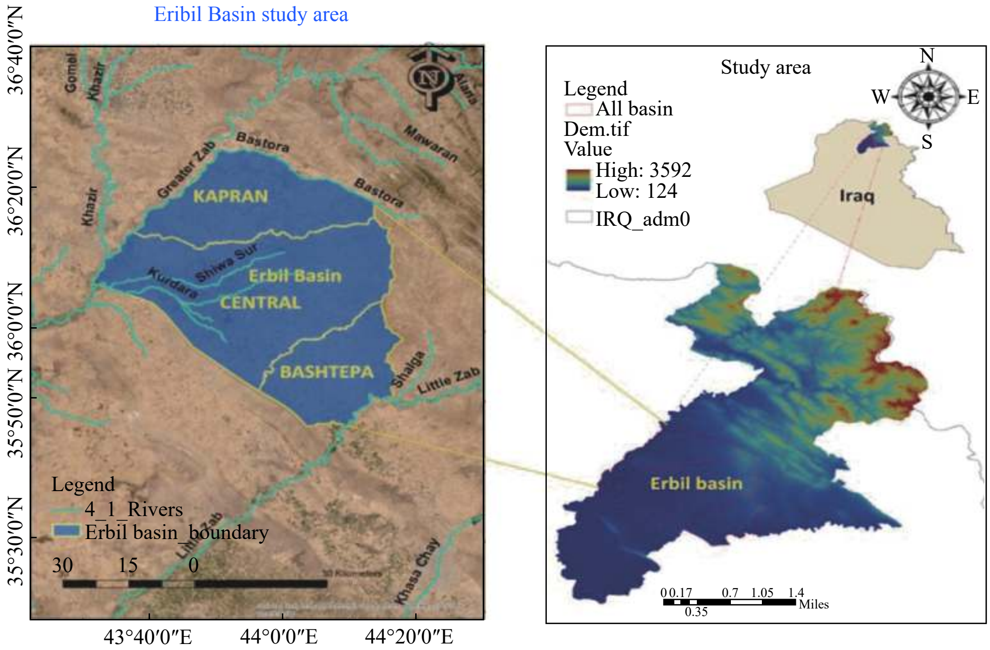

Fig. 1 Location of the study area (Erbil Basin)

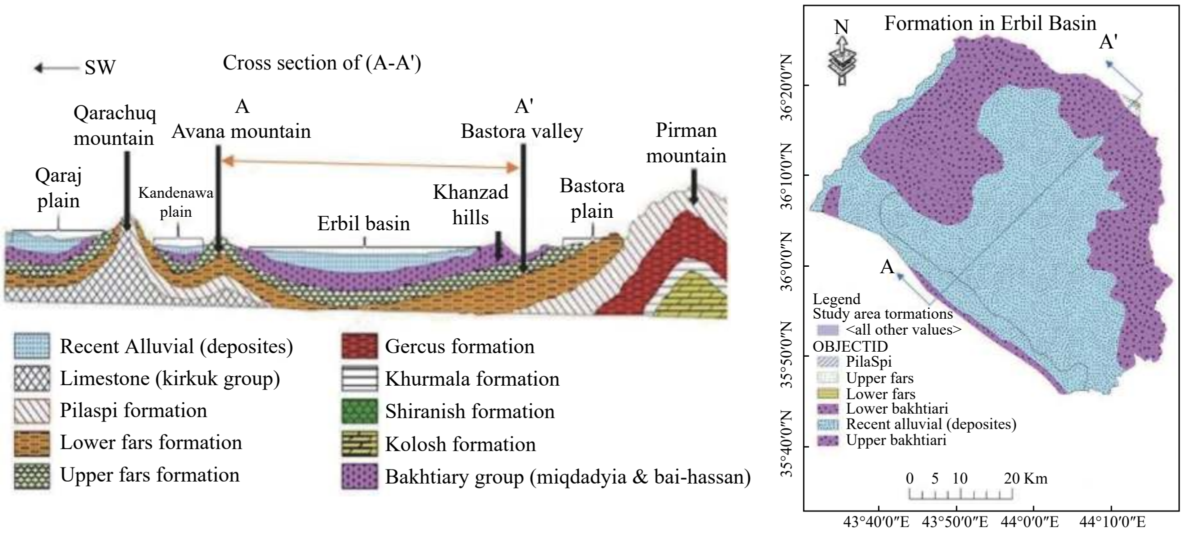

Fig. 2 Geological Formations of Erbil basin modified after (Shekhmamundy and Surdashy, 2022)

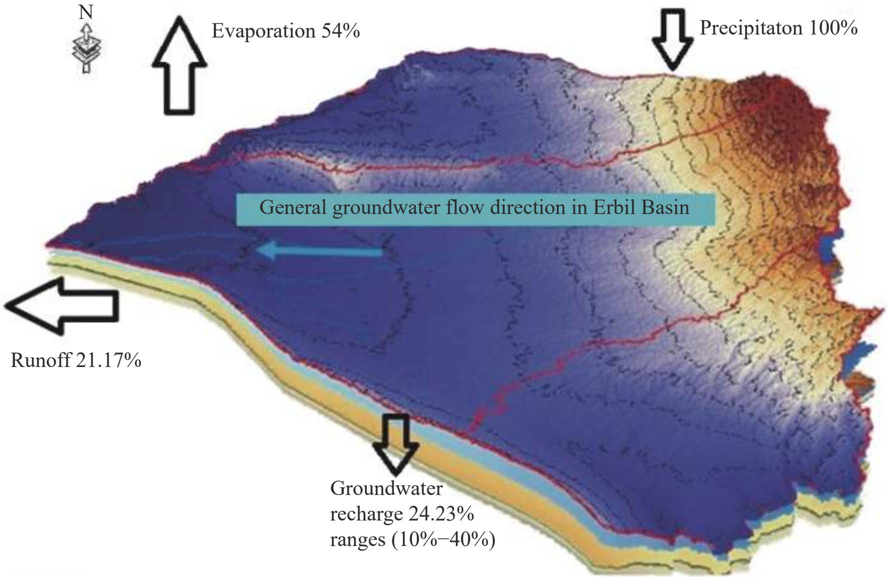

Fig. 3 The information on average rainfall, recharge, runoff, evaporation of Erbil Basin

2015). Advanced groundwater modeling software, including the Groundwater Modeling System (GMS) and MODFLOW 2000, have been developed to facilitate the creation of numerical models by hydrogeologists and engineers. GMS employs a conceptual model approach, enabling users to construct 3D groundwater flow models for various aquifers. GIS objects are frequently employed to prepare input data for these models. Additionally, GMS offers sophisticated subsurface characterization tools, such as cross-section editing and advanced probability statistics, enhancing the precision and comprehensiveness of groundwater modeling efforts (Al-Areedhi, 2019). According to Anderson et al. (2015), the general three-dimension groundwater flow equation for heterogeneous and anisotropic transient condition is as shown in Equation (1):

$$\partial/\partial \mathrm{x}(Kx\partial \mathrm{h}/\partial \mathrm{x})+\partial/\partial \mathrm{y}(Ky\partial \mathrm{h}/\partial \mathrm{y})+\partial/\partial \mathrm{z}(Kz\partial \mathrm{h}/\partial \mathrm{z})=S\,s\partial \mathrm{h}/\partial \mathrm{t}-N \qquad (1)$$

Groundwater flow equation in steady state condition, heterogenous and anisotropic is presented in Equation (2):

$$\partial/\partial \mathrm{x}(Kx\partial \mathrm{h}/\partial \mathrm{x})+\partial/\partial \mathrm{y}(Ky\partial \mathrm{h}/\partial \mathrm{y})+\partial/\partial \mathrm{z}(Kz\partial \mathrm{h}/\partial \mathrm{z})=0 \qquad (2)$$

Where: N is sources and sinks of water (L^3T^{-1}); q (x, y, z) is the Darcy's flux in (x, y, z) directions (LT^{-1}); K is hydraulic conductivity (LT^{-1}); h is hydraulic head (L); Ss is a specific storage of the porous material (L^{-1}); t is time (T).

In this study, the equation for steady-state groundwater flow, considering heterogeneity and isotropy, is applied using GMS software version 10.7. The methodology begins with data collection from 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. Subsequently, the raw data is processed using GIS program to prepare it for input into the GMS software for building the conceptual model. GMS is utilized to simulate the steady states groundwater flow conditions using the MODFLOW 2000 solver package based on finite difference techniques (Al-Areedhi, 2019). See an overview of the main steps of the groundwater flow modeling in Fig. 4.

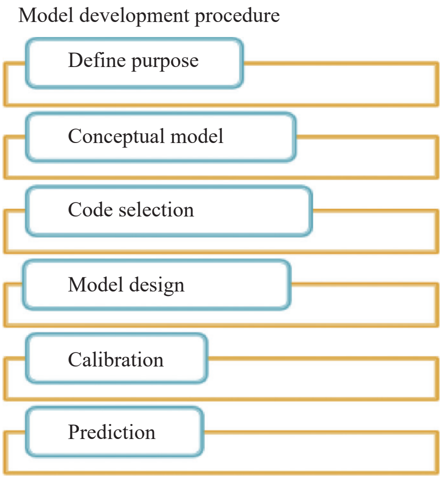

Fig. 4 Flow chart of the study and GMS applications

2.2 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 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, which are essential components providing 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 (Al-Areedhi, 2019). 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.

2.3 Model grid and boundary conditions

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 (Al-Areedhi, 2019). 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. This illustrates the 3D grid structure of the model, providing a visual representation of the aquifer types and their spatial arrangement within the Erbil Basin is shown in Fig. 5.

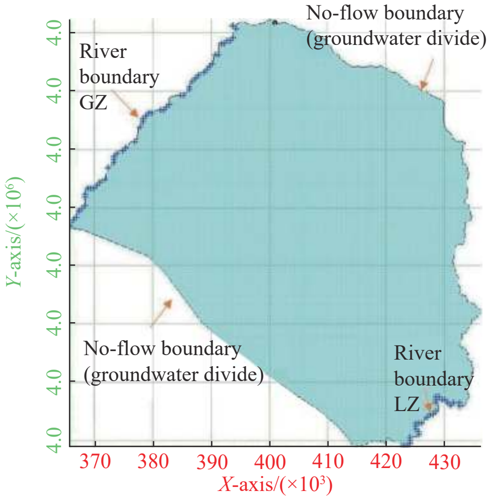

Fig. 5 The boundary conditions used in the study

In addition, the detail about assigning the input data is summarized in Table 1.

2.4 Building the steady-state numerical model

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 28 m × 28 m. This DEM provides a relatively precise surface elevation of the Erbil Basin. Notably, the bottom of the entire model aligns with the bottom of the drilled wells, capturing the subsurface configuration (Al-Areedhi, 2019). The model effectively delineates the characteristics of the unconfined aquifer types within the Erbil Basin, as shown in Fig. 6.

In addition, based on the geological formations within Erbil Basin, the initial hydraulic conductivity values were adopted from Freeze and Cherry (1979), as listed in Table 2.

3 Results and discussion

3.1 Running steady-state model

In the Erbil model, the groundwater 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 groundwater head characteristics due to the complex nature of the aquifer system. A steady-state model was run to achieve the head distribution as shown in Fig. 7. A calibration approach is required to match the simulated head with the measured head in the observation wells.

Whereas, the velocity vector obtained from the model results are Fig. 8.

3.2 Model calibration using PEST and pilot points

Table 1 Input data for MODFLOW 2000 package in GMS software

Conceptual model	Descriptions of the items
Model domain	Cell sizes (500 m by 500 m) by 600 m as thickness of the aquifer
Boundary condition	River's conductance = 2.74 and 2.29 m^2/d for Greater and lesser Zab Rivers, respectively Greater Zab River upstream head stage = 279 m and river bottom 277 m Downstream node GZ= 215 m and 213 m Lesser Zab River upstream head stage = 270 m and river bottom 268 m Downstream node = 252 m and 250 m
Aquifer types coverage	Define hydraulic conductivity for each aquifer type in LPF package
Recharge coverage (RCH)	Recharge cells are defined by the polygon of the model area (RCH) with initial recharge rate of 0.000385 m/d, approximately 10% to 40% of average annual rainfall. Surface water bodies are also included.
Existing wells coverage	Number of the production wells: 8384

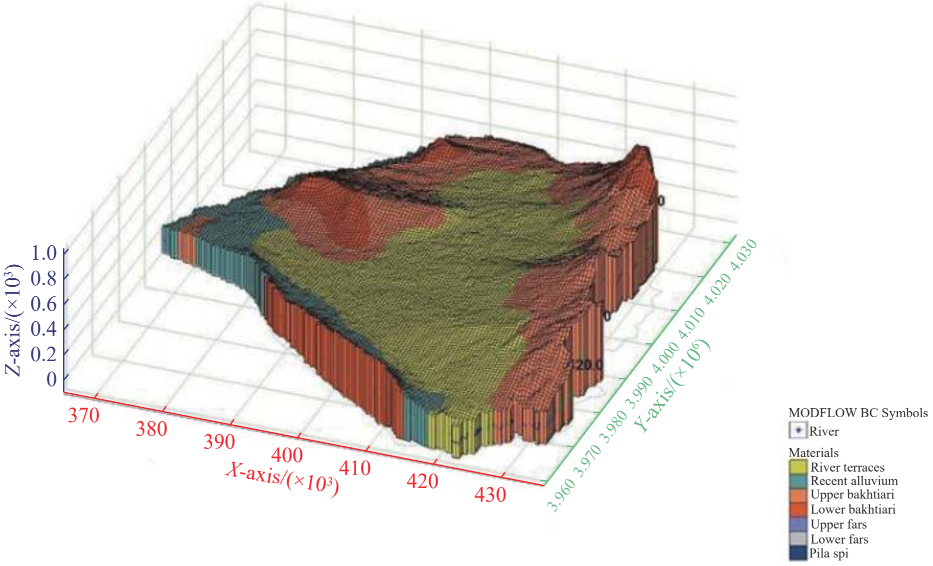

Fig. 6 Model structure and delineation of Aquifer types (geological formations)

Table 2 The Hydraulic conductivity ranges (Freeze and Cherry, 1979)

Descriptions of the rock types	K_{min} /m/d	K_{max} /m/d
Unconsolidated deposits		
Coarse gravel	864	8,640
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

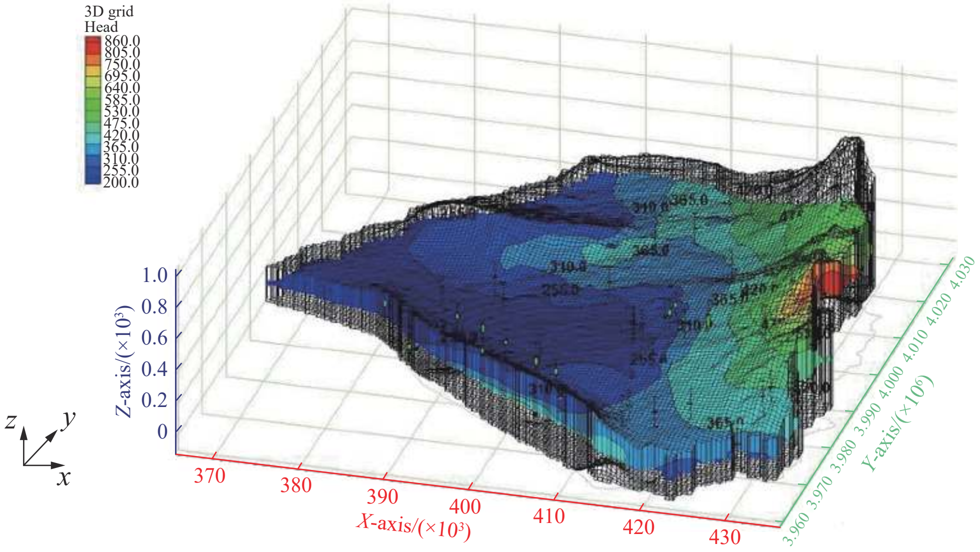

Fig. 7 The contour map of groundwater head

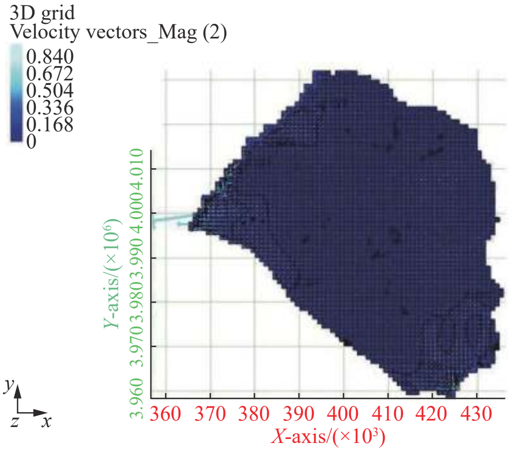

Fig. 8 Distribution of the velocity vector over the model area

The primary objective of model calibration is to minimize the discrepancy between observed and simulated groundwater head values by adjusting model parameters. This alignment is crucial for ensuring that the model accurately reflects the actual behavior of the groundwater system. Calibration can be conducted manually through trial and error, or more systematically using automated approaches like PEST and pilot points in GMS. The effectiveness of calibration relies on a thorough characterization of field conditions at the site (Al-Areedhi, 2019). In the Erbil model, the calibration result demonstrates a harmonious match between observed and simulated head values, indicating successful calibration in capturing the intricacies of the groundwater flow in the studied area as depicted in Fig. 9.

Following the model run, it is common that the obtained results may 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. To minimize these differences, Calibration process is conducted and invo-

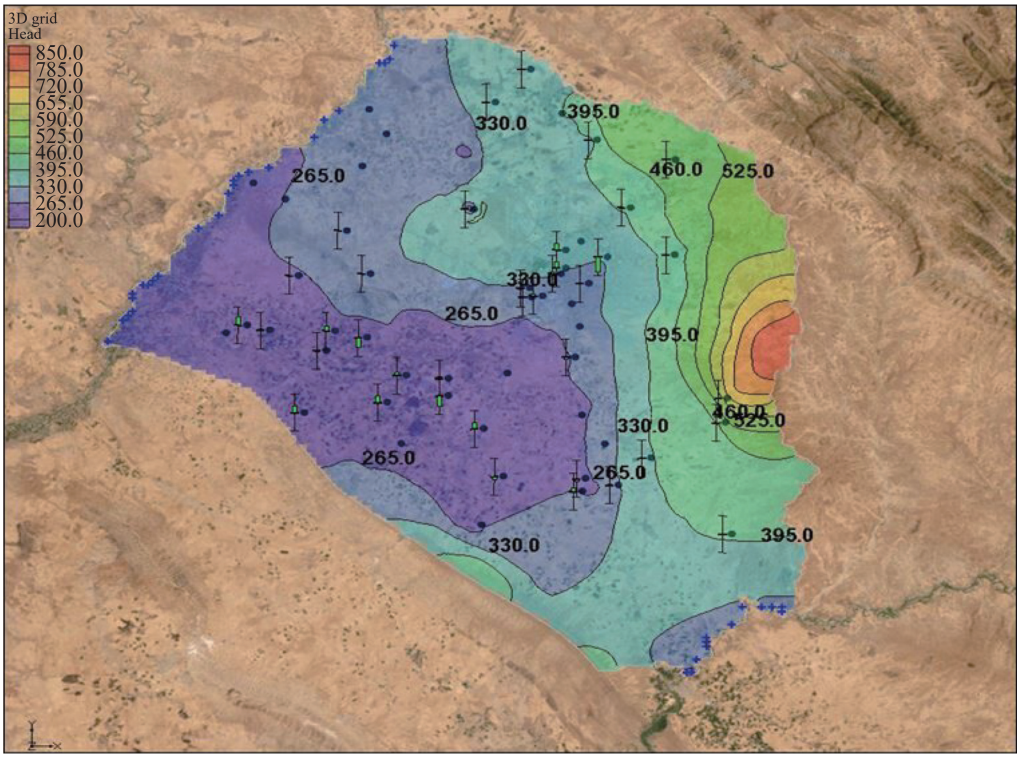

Fig. 9 The groundwater modeling head distribution

lves adjusting model parameters, such as Hydraulic conductivity (HK), recharge (RCH), and other parameters, 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 and reliability, ensuring that it captures the characteristics of the groundwater flow in the studied area.

To evaluate the calibration results, the observed groundwater head is considered 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:

Mean Error Equation:

$$ME = \frac{1}{2}\sum\nolimits_{i=1}^{n}(h_{observed} - h_{simulated})_i \tag{3}$$

Mean Absolute Error:

$$MAE = \frac{1}{2}\sum\nolimits_{i=1}^{n}/h_{observed} - h_{simulated}/_i \tag{4}$$

Root Mean Square Error:

$$RMSE = \sqrt{\frac{1}{2}\sum\nolimits_{i=1}^{n}(h_{observed} - h_{simulated})_i^2} \tag{5}$$

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 (MacDonald and Arlen, 1988). 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 (Anderson et al. 2015). 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 (Fig. 10).

In this study, the minimization of errors in the groundwater model was achieved through the application of pilot points used with PEST, 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 pilot points, the study aimed to enhance the accuracy of hydraulic conductivity values in the calibrated model (Al-Areedhi, 2019). The statistic results of the application of PEST are summarized in Table 3.

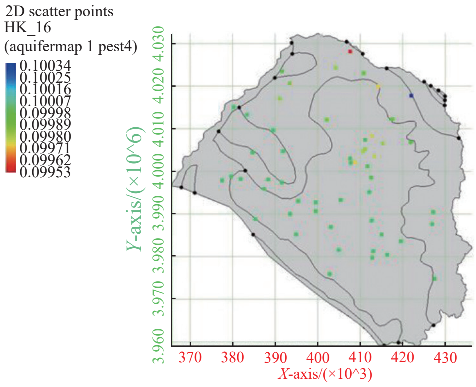

Fig. 10 Pilot points used for PEST calibration

Table 3 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

Fig. 11 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. The closer the points align to the line, means the better the model's predictive capability, indicating a successful calibration and validation process as shown in Fig. 11.

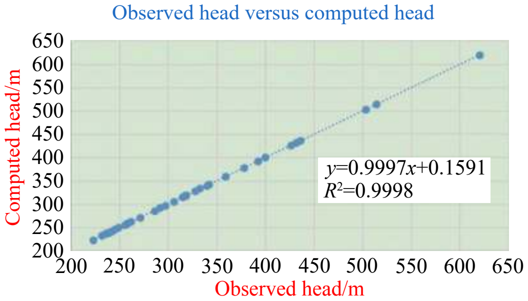

Fig. 11 Plot of the observed head versus simulated head

3.3 Sensitivity analysis

The sensitivity analysis compares model results and parameters for both the calibration period and future scenarios. It involves fixing all calibrated parameters except the selected ones to determine which parameters have the greatest impact on the model results (MacDonald and Arlen, 1988). Parameters with high impact on the model results require more attention during the calibration process and data collection. The most common method of sensitivity analysis involves using finite difference methods to estimate the rate of change in model results due to changes in parameters (Anderson et al. 2015). In this study, trial-and-error methods were initially used, followed by the utilization of automated parameter estimation method, PEST and pilot points to analyze parameter sensitivities (Al-Areedhi, 2019), as shown in Fig. 12.

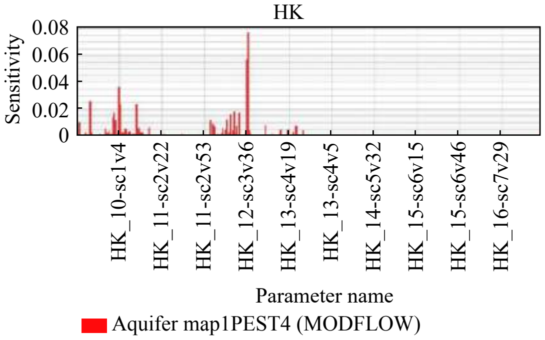

Fig. 12 Parameter sensitivity of the hydraulic conductivity values used for PEST pilot points

3.4 Water budget

Water budget analysis was conducted to calculate 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 occurred through production water wells and rivers, representing losses from the system. This information is crucial for effective water resource management and informs decision-making processes related to the sustainable use of groundwater in the region. The details of water budget in the Erbil model is summarized in Table 4.

The information presented in Table 4 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.

The result head from the calibrated model is depicted in Fig. 8, illustrating the hydrogeological conditions within the Erbil Basin. Bounded by the

Table 4 Water budget information

Descriptions	**Flow in /m^3/d**	**Flow out /m^3/d**
Wells	0	−840,230.40
River Leakage	10,237.45	−78,636.69
Recharge	910,633.68	0
Total Source/Sink	920,871.13	−920,871.09
Zone Flow		
Total Flow	920,871.13	−920,871.09
Summary	In - Out	% difference
Total	0.040	4.35E^{-06}

Greater and Lesser Zab rivers in the northwest and southwest, and constrained by Bastora chay and Basti shalgha in the northeast, the model highlights distinct recharge zones in the western and smaller eastern hills where geological formations outcrop. The low hydraulic conductivity of the Upper Bakhtiari Formation is evident, leading to noticeable drawdowns in extraction well locations, particularly near Erbil. This characteristic results in a steep gradient in the southern outflow segments, inconsistent with expected shallow conditions based on measured data. The study identifies a lack of groundwater management in the region, primarily due to over-exploitation 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. According to unsaturated zone effect on the Erbil basin groundwater, the neglect of evapotranspiration occurred because the depth of the aquifer and groundwater table was below the extinction depth. This means that at this depth, the water table stops being affected by evapotranspiration (Chiang, 2010). The study concludes that average groundwater recharge values range between 0.375 mm/d and 0.376 mm/d. Model calibration utilized trial and error, PEST and 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 0.9998 underscores the model's excellent correspondence with field observations, as depicted in Fig. 11. Additionally, the average groundwater flow velocity is estimated at approximately 0.008459 m/d, 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.

4 Conclusion

In conclusion, the 3D groundwater flow modeling for the Erbil groundwater basin represent a significant first step in understanding the hydrological dynamics of the region. This study stands out as the initial investigation into the groundwater basin of Erbil, filling a crucial gap in knowledge where no prior studies have delved into its specifics. By employing advanced modeling techniques and conducting a comprehensive water budget analysis, valuable insights have been gained into the complex interplay of factors influencing groundwater flow and availability in the region. The findings of this study not only provide a foundational understanding of the Erbil groundwater basin but also lay the groundwork for future research and management strategies aimed at sustainable water resource utilization and conservation in the area.

The 3D groundwater flow modeling of the Erbil Basin holds immense potential for guiding future scenarios and enhancing our understanding of the aquifer system's actual behavior. This modeling approach offers a robust framework to simulate various hypothetical scenarios, allowing stakeholders to assess the potential impacts of different management strategies, climate change scenarios, and water usage patterns on groundwater resources. By incorporating real-time data and accounting for complex hydrogeological factors, such as recharge rates, aquifer properties, and extraction rates, the model can provide valuable insights into the dynamics of the aquifer system. Such insights are crucial for informing sustainable management practices that balance the competing demands of water supply, agricultural needs, and environmental conservation. Therefore, the utilization of 3D groundwater flow modeling represents a proactive and effective tool for ensuring the long-term sustainability of water resources in the Erbil basin and beyond.

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