JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2024, 25(4), 203–227
https://doi.org/10.12911/22998993/184184
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Received: 2024.02.01
Accepted: 2024.02.20
Published: 2024.03.01

Assessment of the Groundwater in Erbil Basin with Support of Visual MODFLOW

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ABSTRACT

Groundwater stands as a crucial lifeline in numerous regions across the globe, a significance magnified in water-scarce locales like the Middle East. With depleting water resources exacerbated by global climate change, the imperative for sustainable groundwater management becomes increasingly urgent. This research employs a groundwater flow modeling approach, utilizing Visual MODFLOW (version 4.6.0.166), to scrutinize the present state and future security risks of groundwater resources in the Erbil basin. A distinct aspect of this study involves investigating the interaction between the groundwater aquifers of Greater Zab and Lesser Zab Rivers, along with an exploration of the Erbil aquifers, rivers interaction and recharge zones as a second novelty in this research. The model, calibrated for heterogenous anisotropic unconfined aquifer transient conditions, exhibits a high correlation coefficient (CC) of 0.997 during calibration and 0.985 in the validation process respectively. Findings indicate a general groundwater flow direction from northeast to southwest in the Erbil basin, aligning with surface observations. Despite groundwater aquifers supplying only 55% of the current water demand from the existing wells, the computed balance reveals river leakages of 33,432 m^3/day into the aquifers. The study forecasts a substantial increase in the dry area of the groundwater aquifer under climate change scenarios, especially when recharge rates diminish. To mitigate these impacts, the study recommends preventing illegal well drilling and implementing continuous monitoring using distributed sensors. The insights gleaned from this research are anticipated to furnish essential information for sustainable planning and effective management of groundwater resources in the Erbil basin and its environs.

Keywords: analyzing the groundwater; Erbil Basin; groundwater flow modeling; visual MODFLOW.

INTRODUCTION

This study is important because it comprehensively investigate and enhance the management strategies for groundwater resources in the Erbil Basin. With a focus on sustainable development and environmental conservation, the study seeks to evaluate the current state of the groundwater basin, identify potential challenges, and propose effective management practices. Erbil Basin, being a crucial water source for the region, faces increasing demands due to population growth and economic activities. The importance of this study lies in its potential to provide valuable insights and practical solutions for sustainable groundwater use, ensuring the long-term availability of this vital resource while mitigating the risks associated with over-extraction and environmental degradation. Implementing effective groundwater management strategies can contribute significantly to the overall well-being and resilience of the Erbil community, fostering socio-economic development and environmental sustainability. Groundwater models play a crucial role in informing management decisions related to groundwater quantity and quality. The choice of model extent, approach, and type depends on the specific objectives of the modeling effort. There are three main categories of groundwater models: interpretive, predictive, and generic. Interpretive models are tailored to study specific cases, allowing for in-depth analysis of groundwater flow or contaminant transport within a particular context. Predictive models, on the other hand, are designed to project changes in groundwater head or solute concentration over time, providing insights into future scenarios. Lastly, generic models are versatile tools used to analyze various scenarios related to water resource management or remediation schemes, offering a broader perspective on potential strategies for sustainable groundwater use and environmental protection. The versatility of these models enhances their utility in addressing diverse challenges associated with groundwater management [1,2].

There are many studies on groundwater flow modeling such as; the study which suggests an investigation into the groundwater dynamics in the Khanaqin area of Northeast Iraq using modeling techniques. The study likely explores the complex interplay of geological, hydrological, and climatic factors affecting groundwater flow in this region. This type of research is crucial for understanding water resource management and ensuring sustainable use of groundwater. The findings may have implications for local communities, agriculture, and environmental conservation [3].

Likely another study focuses on assessing the sustainability of an aquifer in a specific region. By employing groundwater flow modeling techniques, the research aims to understand the dynamics of the aquifer in Choutuppal Mandal, Nalgonda District, Telangana, India. This investigation is essential for managing and preserving groundwater resources, especially in regions facing increasing demands for water due to population growth and agricultural activities. The study may explore factors influencing groundwater flow, such as geological characteristics, land use patterns, and climatic conditions. The results of this research could provide valuable insights for local authorities, policymakers, and communities, contributing to informed decisions regarding water resource management and sustainability in the specified area [4]. Also, another study used investigates strategies and practices for the sustainable utilization of groundwater in the specified region. Given the importance of groundwater in arid environments like West Iraq, the research may address issues such as aquifer recharge, extraction rates, and potential threats to groundwater quality. Effective management of groundwater resources is critical for sustaining agricultural activities, supporting local communities, and mitigating the impacts of climate variability. The study is likely to provide insights and recommendations for optimizing groundwater use, enhancing water security, and addressing challenges associated with the management of this vital natural resource in the Dhabaa site of West Iraq [5]. Another study focuses on employing Visual MODFLOW for groundwater modeling. The use of Visual MODFLOW indicates a commitment to advanced modeling techniques for understanding and managing groundwater systems. Visual MODFLOW is a widely used software tool in hydrogeology, allowing for the simulation of groundwater flow and the assessment of various scenarios [6]. The application of conformal mapping to two-dimensional flows in an anisotropic aquifer signifies a sophisticated approach to understanding groundwater dynamics. Conformal mapping, a mathematical technique that preserves angles between curves, is employed to analyze the complex behavior of fluid flow within an anisotropic aquifer. Anisotropy in this context refers to the directional variation in hydraulic conductivity within the aquifer. By utilizing conformal mapping, researchers can gain valuable insights into the spatial variations and intricate patterns of groundwater flow in two dimensions. This method holds significance for hydrogeologists and water resource managers seeking a comprehensive understanding of anisotropic aquifer systems, aiding in the development of effective strategies for sustainable groundwater management and resource utilization [7]. The study likely employs modeling techniques to analyze the intricate patterns and factors influencing groundwater movement in this specific geological setting. The Journal of Nepal Geological Society is a reputable platform for geological research, indicating the scholarly significance of the work. The paper likely contributes to the understanding of hydrogeological processes in intermontane basins, providing valuable insights for researchers, policymakers, and water resource managers in Nepal and potentially beyond [8]. Likely, another study that explores the application of GMS (Groundwater Modeling System) software in predicting groundwater levels, focusing specifically on the Karvan area in Iran. GMS is a specialized tool used for groundwater modeling, allowing for the simulation and analysis of subsurface water flow. This research is likely to involve the integration of geological and hydrological data into the software to develop a predictive model for groundwater levels in the Karvan region. The case study approach indicates a practical application, providing insights into the potential of GMS software for accurate groundwater level predictions in this specific geographical context. The findings of this study may contribute to improved water resource management strategies and sustainable groundwater use in the Karvan area of Iran [9]. A study provides a comprehensive overview of various modeling approaches and strategies employed in the management of groundwater resources. Such a review would likely assess the current state of the field, highlighting key methodologies, challenges, and advancements in groundwater management modeling. This type of study is essential for synthesizing existing knowledge, identifying gaps in research, and offering insights that can inform effective groundwater resource management practices [10-13].

As well as, there are numerous studies worldwide have undertaken the investigation of groundwater flow modeling and associated challenges, employing the widely utilized MODFLOW software. These studies span diverse countries and regions, reflecting a concerted effort to address groundwater management and planning issues. By harnessing the modeling capabilities of MODFLOW, researchers seek to simulate and understand the complex dynamics of groundwater flow in various hydrogeological settings. The application of MODFLOW in different contexts highlights its versatility as a tool for developing solutions to water resource management challenges. These studies play a crucial role in informing effective planning strategies, offering insights that contribute to sustainable groundwater use and aiding decision-makers in crafting policies tailored to the specific needs of their respective regions. The collective knowledge generated from these investigations serves as a valuable resource for advancing global best practices in groundwater management and planning [13-24]. Moreover, the continuous decline in groundwater levels, attributed to unregulated extraction from both legal and illegal wells, presents a significant challenge in the selected basin. This issue is particularly pronounced in the context of the area being classified as arid and semi-arid regions. In order to address this pressing concern, accurate predictions of groundwater table maps are deemed essential. These predictions are crucial for the development of effective groundwater management strategies tailored to the specific aquifer system in the study area. By understanding the spatial distribution and trends in groundwater levels, authorities can formulate informed policies to mitigate over-exploitation, promote sustainable water use, and safeguard the long-term viability of the aquifer in this arid and semi-arid region [25-28].

Groundwater in the last two decades become a crucial subject for the scientific and the researchers in Kurdistan region of Iraq. do the huge impact of the climate change increase the population and demand of the groundwater in the region new technology and modeling is vital to understand the management of the groundwater to optimize the use of groundwater in the area. to prevent near future declining of groundwater if there is no immediate certain measurement consider. Therefore, the primary aim of this study was to development of a groundwater flow model for the Erbil Basin, as no prior research had focused on this specific area. Recognizing the absence of previous studies, the research sought to fill this gap by creating a comprehensive model that could contribute significantly to the understanding and management of groundwater resources in the region. By establishing a foundational groundwater flow model, the study aimed to provide essential insights for effective planning and sustainable development of groundwater in the Erbil Basin. The absence of prior investigations underscored the importance of this research, positioning it as a pioneering effort to address critical gaps in knowledge related to groundwater dynamics in this particular geographical context.

MATERIALS AND METHODS

Study area

The Erbil Basin, situated in the northern part of Iraq, are bordered by the Greater Zab (GZ) and Lesser Zab (LZ) rivers, extending from North to South. The basin is further divided into three hydrogeological sub-basins known as KAPRAN, CENTRAL, and BASHTHEPA. Encompassing a total area of 3,200 square kilometers, the Erbil Basins hold geographical coordinates between a longitude (E) of 44.00° and a latitude (N) of 36.19°, with an elevation of approximately 420 meters above sea level. The climate in this region is characterized as arid and semi-arid, categorized as hot and dry during summers and cold and wet in winters. The intricate hydrogeological and climatic features of the Erbil Basins make it a critical area for water resource management and necessitate a detailed understanding of its groundwater dynamics for sustainable development in the region [26, 27]. The Erbil Basin is geographically delineated by distinctive natural boundaries. To the north, it is bordered by the Bastora basin, while the Demir anticline marks its southern boundary. The western and northwestern borders are formed by the Greater Zab River, while the eastern periphery is defined by the Sharabot hills (Figure 1).

The hydrogeological conditions of the Erbil Basin are intricately tied to its tectonic characteristics, marked by a series of synclines and anticlines. In tectonic terms, Erbil city is situated directly above a syncline, forming a basin-like structure. The basin's northern and southern borders are defined by anticlines, resulting in elevated terrain. These anticlines play a role in exposing lower-lying geological layers at the surface. The Erbil plain is positioned within the Low Folded Zone, encompassed by the Pirmam anticline and Bastora stream to the north, and the Dimer anticline and Shamamk plain to the south. To the west, the Greater Zab River acts as a natural boundary, while the eastern border is formed by hills and the Shalghah Bestana area. The geological map of Iraq, and further illustrates the diverse geological features that contribute to the unique hydrogeological setting of the Erbil Basin. Understanding these tectonic and geological nuances is crucial for effective groundwater management and sustainable development initiatives in the region [29, 30]. The detail of the geological formations and cross-section is illustrated in Figure 2.

The above Figure 2 is geological formations and the modified cross-sectional described [29, 30]. The delineation of these geographical and geological features is crucial for understanding the hydrogeological dynamics of the Erbil Basin and is instrumental in the formulation of effective strategies for its sustainable management and development.

Methodology of groundwater flow modeling

The groundwater flow simulation in the study area is conducted using Visual MODFLOW, a platform that incorporates the modular 3D finite-difference groundwater flow code [31]. This numerical approach is commonly employed to simulate groundwater flow in both local and regional groundwater systems [32]. The simulation is guided by the groundwater flow equation (Equation (1)), a fundamental equation used in MODFLOW. This equation enables the understanding of groundwater flow in three distinct directions, providing a comprehensive analysis of the subsurface water movement in the specific hydrogeological context under consideration. The utilization of Visual MODFLOW and its integration with established numerical codes demonstrates a sophisticated approach to modeling groundwater dynamics, offering valuable insights for groundwater resource management and planning in the studied area [33].

$$\frac{\partial}{\partial x}\left(Kx\,\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Ky\,\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kz\,\frac{\partial h}{\partial z}\right)=Ss\,\frac{\partial h}{\partial t}-\mathrm{R}\,(1)$$

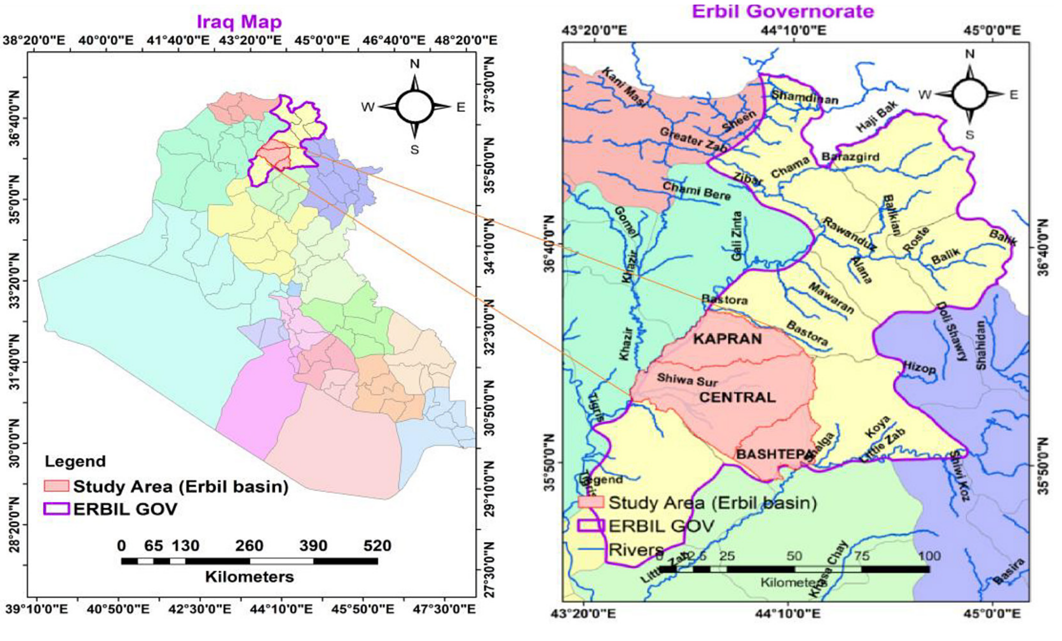


Figure 1. Location of the Erbil Basin study area

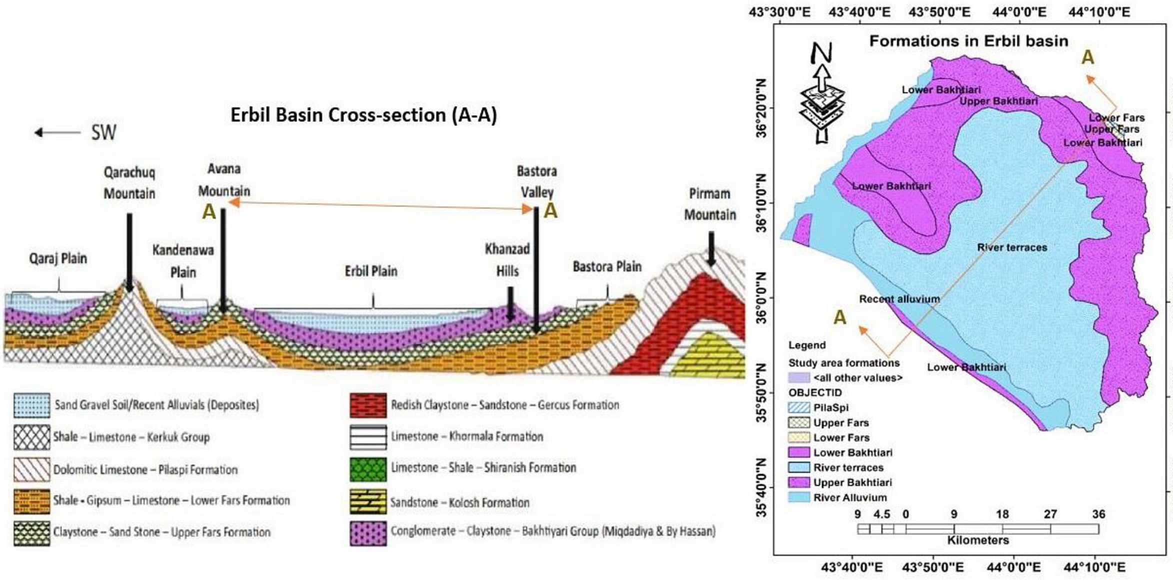


Figure 2. The detail of the geological formations of the basin

Table 1. The descriptions of the geological formation with the material classifications [29, 30]

No.	Formation types	The compositions of each formation's materials
1	Quaternary deposits	rock fragments, gravelly, silty, sandy
2	Upper Bakhtiari (Bai Hassan)	conglomerate, sandstone, claystone
3	Lower Bakhtiari (Mukdadiyah)	pebbly sandstone, siltstone, claystone
4	Upper Fars (Injana)	sandstone, siltstone, claystone
5	Lower Fars (Fatha)	gypsum, marl limestone, siltstone, claystone
6	Pilaspi	well bedded limestone
7	Gercus	sandstone, siltstone, claystone

In the context of groundwater flow simulation using Visual MODFLOW, the mathematical representation involves parameters such as hydraulic conductivity (Kx, Ky, and Kz) representing the conductive capacity in three distinct directions. Other essential variables include specific storage (Ss), hydraulic head (h), and sink or source terms denoted by R. The governing finite-difference mathematical equation (Equation (2)) forms the basis for Visual MODFLOW's simulation framework. The assumptions underlying this equation encompass conditions of constant density and viscosity for groundwater flow, specifically during transient state conditions [34]. This finite-difference approach, incorporating these parameters and assumptions, enables Visual MODFLOW to provide a robust and dynamic simulation of groundwater movement in diverse hydrogeological scenarios. The software's capacity to model transient state conditions makes it particularly valuable for studying the evolving dynamics of groundwater systems over time, contributing to a comprehensive understanding of subsurface water behavior.

$$kx\left(\frac{\partial^2 h}{\partial x^2}\right)+ky\left(\frac{\partial^2 h}{\partial y^2}\right)+kz\left(\frac{\partial^2 h}{\partial z^2}\right)\pm W=S_s\frac{\partial h}{\partial t} \quad (2)$$

Visual MODFLOW offers a range of solvers to effectively address the numerical equations involved in groundwater flow simulations. These solvers include the preconditioned conjugate gradient (PCG), strongly implicit procedure (SIP) package, WHS solver specific to visual MODFLOW (WHS), slice successive over relaxation (SOR) package, and the geometric multigrid solver (GMG) package. Each solver is designed to handle different aspects of the groundwater flow simulation process, providing flexibility and adaptability to diverse modeling scenarios. The use of these solvers contributes to the accuracy and efficiency of the simulation, allowing for the exploration of various groundwater flow conditions and enhancing the capabilities of Visual MODFLOW in addressing complex hydrogeological challenges [19]. For this study Newton Raphson Solver (NWT) solver package, which always available in case of using MODFLOW- NWT type that is used to solve the partial differential equations through iterative procedures.

Developing groundwater numerical model

The groundwater modeling process initiates with the creation of a groundwater flow model that accurately represents the physical conditions of the study area. In alignment with this approach, the current study has devised a model featuring a single layer, reflecting the geological and lithological characteristics, river boundary conditions, and groundwater level datasets. Specifically, the modeled single layer encapsulates the deep unconfined aquifer, comprised of unconsolidated formations up to a depth of 700 meters. Once the conceptual model is formulated, it is translated into a numerical model using the Visual MODFLOW 4.6.0.166 as a user interface of the software of numerical groundwater model "MODFLOW" of the U.S. Geological Survey (USGS), and USGS MODFLOW-NWT as formulation of MODFLOW-2005 to improve solution of unconfined groundwater-flow problems. This transition involves a series of steps to ensure a robust representation of the hydrogeological system. The input parameters utilized in the conceptual model are outlined in Table 2, serving as the foundation for the subsequent numerical simulations and analyses.

Table 2. Input data and modeling parameters

No.	Parameters	Description
1	Model domain	3,100 km^2
2	Grid sizes	500 × 500 m
3	Aquifer thickness	700 m
4	Aquifer type	Unconfined aquifer
5	Flow condition	Heterogeneous anisotropic
6	Modeling state	Transient state
7	Boundary conditions	No flow boundary
8		River
9		Drain
10	Number of wells	8342 wells
11	Observation wells	16 wells
12	Calibration periods	One years (CC = 0.997)
13	Validation periods	Two years (CC = 0.985)
14	Recharge boundary	Variable
15	Initial head	Steady state head
16	Model angle	315 degree
17	Steady-state	1 Jan. 2023
18	Transient state	2022 to 2024

Model domain

The model study area covers 3,100 km^2 and is gridded into cells with 126 rows (I = 126) and 150 columns (J = 150) and each cell consists of 500×500 m blocks. The modeled layer thickness varies approximately 700 m in the study area. layer elevation and ground elevation data are imported in Visual MODFLOW. As shown in Figure 3.

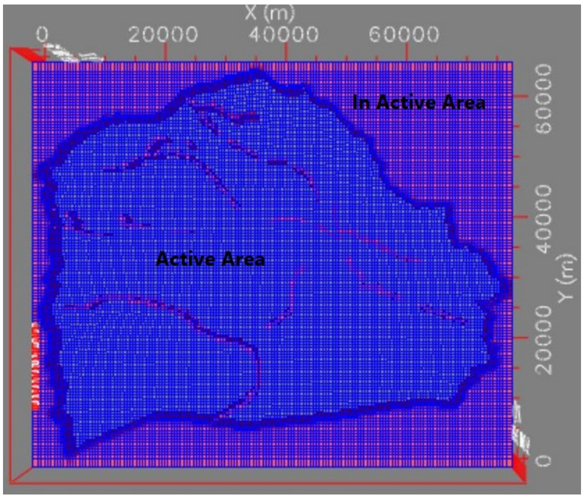


Figure 3. Details of the model domaingrids

Observation head (hydraulic head)

Hydraulic head data of 16 different monitored wells were collected from the Directorate of Erbil Ground Water, General Directorate of Water Resources, Ministry of agricultural and water Resources in Erbil basin aquifer system for this study. The depth to groundwater varies from 23.4 m to 157.5 m. For groundwater flow simulation, 1 January 2023 has been taken as the initial time. Monthly data of the twelve different periods of head data (from the year 2022 to 2024) have been used for both calibration and validation of the model.

The study has a well-organized approach to collecting observational data for groundwater levels. By obtaining time series data from field measurements conducted by the Directorate of Erbil Groundwater, to ensure that the study has reliable and real-world information about the groundwater levels over time. Accordingly, the use of high-resolution surveyor instruments to determine the precise locations of wells within the model domain further enhances the accuracy of your data. This information allows to effectively integrate observational data with groundwater dynamics simulation model and compare the simulated results with the observed data. By aligning the distribution of wells with the model domain, it can be accurately represent the spatial distribution of groundwater levels within the simulation. This integration of observational data and model representation helps validate the model's performance and ensures that it accurately reflects the real-world behavior of the groundwater system in the Erbil region. The locations of the calibrated wells inside model domain shown in Figure 4.

For calibration and validation process 16 observation heads used, and for uncertainty 29 wells used for Erbil Basin groundwater modeling

Recharge rate

The hydrogeological study incorporated a dynamic element by employing a variable recharge rate across the model area. This signifies a recognition of the spatial heterogeneity in recharge characteristics within the aquifer system in the Erbil basin. The incorporation of variable recharge rates allows for a more realistic representation of the complex hydrological processes influencing groundwater dynamics. By considering the variability in recharge across the model area. the values of the recharge. Accordingly, this study uses the various recharge rates in case of the modeling, it varies approximately between (15–40%) of the average annual rainfall over the region, this range is within the previous studies estimated values such as shown in Table 3. The recharge zones of the study area divided into several zones, each zone used variable recharge rates (Figure 5).

Table 3. The recharge percentage used by the previous studies

Recharge percentage based on rainfall infiltration	References
R = 22.8-24.9%	Hassan, 1981 [35]
R = 24.23%	Hassan, 1998 [36]
R = 9.13%	Shwani, 2008 [37]
R = 9.8-15.8%	Kakaye, 2014 [38]
R = 25-50%	Kareem, 2018 [39]
R= 21.01%	Al-Kubaisi, 2019 [40]
R = 14.36-39.34%	this study

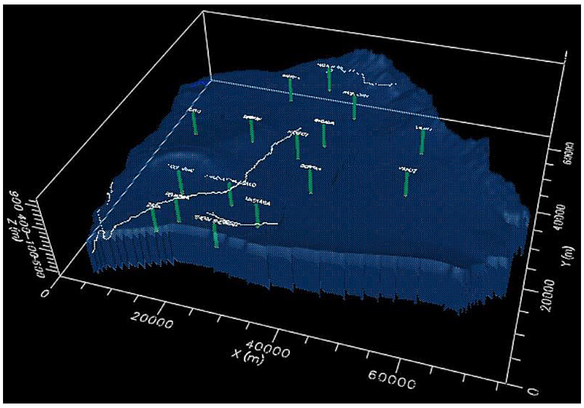


Figure 4. Sapatial distributions of the observation heads used in calibartion process

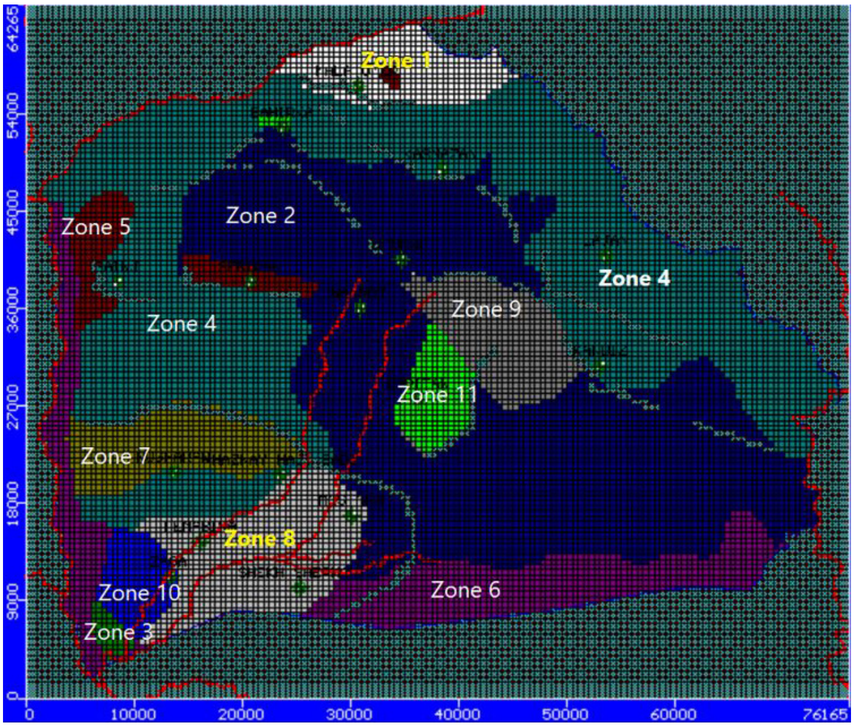


Figure 5. The recharge zones within model domain

Boundary conditions

The Visual MODFLOW simulates the groundwater flow followed by different types of boundary conditions. In the Erbil basin, three types of boundaries conditions have been used [19,31,33]. Three distinct types of boundary conditions have been employed in the modeling process to capture the diverse hydrological features in the study area.

River Boundaries: For the sides of the model area where rivers are present, river boundary conditions have been implemented. This considers the influence of surface water bodies on the groundwater system. At this condition, the river conductance should be calculating according to the following Equation (3):

$$C_{River} = \frac{K_r \cdot L \cdot W_r}{B} \tag{3}$$

where: *Kr* – hydraulic conductivity of the river bed (m/day), *L* – length of the reach/grid size (m), W_r – width of the river (m), *B* – thickness of the river bed (m).

The detail of conductance principle shown in Figure 6. The river bed conductance of two rivers Greater Zab and Lesser Zab is approximately the same, and it is determined as 6 m^2/day. In addition, the assumptions in the Visual MODFLOW program, defining River Package data involves inputting six key parameters for each river reach: the layer, row, and column of the cell containing the reach, the width of the river, river stages at the start and end points, riverbed layer thickness, riverbed layer conductance, and riverbed bottom elevations at the start and end points. During the simulation process for the River Package, a river seepage term is introduced at the beginning of each iteration, which is then added to the flow equation for each cell in the system. A crucial aspect of the simulation involves determining which equation to use for calculating the flow seepage based on a comparison between the most recent values of head at the cell containing the river reach and the value of RBOTn for the reach. RBOTn represents the riverbed bottom elevation. The Visual MODFLOW program selects the appropriate equation for flow seepage calculation based on this comparison [33, 39]:

- No flow boundaries – in areas without significant surface water features, no flow boundaries have been designated. These boundaries imply zones where there is negligible or no exchange of water with the surrounding aquifer. This could be representative of areas where groundwater movement is restricted or where the aquifer is bounded by impermeable layers.
- Drain boundaries – a distinctive feature of the modeling approach is the incorporation of drain boundaries situated in the middle of the model area. Drain boundaries are indicative of areas where water is actively removed from the aquifer, potentially simulating artificial drainage systems or natural features that act as conduits for groundwater outflow [19, 39] (Fig. 7).

The Figure 7 explains that the boundary conditions used in the Erbil Basin modeling, this depiction unveils a meticulous allocation of boundary conditions catering to the distinctive geographical features of the basin. Notably, the right and left sides of the model, intricately associated with the Bastora Chay, are subjected to river boundary conditions. This implies a detailed consideration of the dynamic nature of river systems, incorporating parameters such as water levels, velocities, and potential inflow/outflow rates. Moving towards the north-east and south borders of the model, designated as the groundwater divide, a no-flow boundary condition is implemented. This strategic choice reflects a deliberate

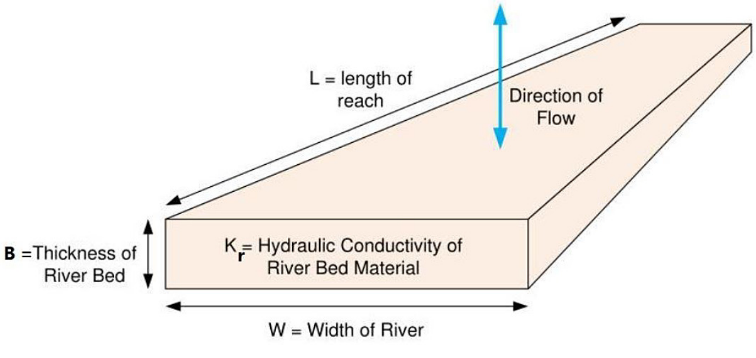


Figure 6. River conductance explanation

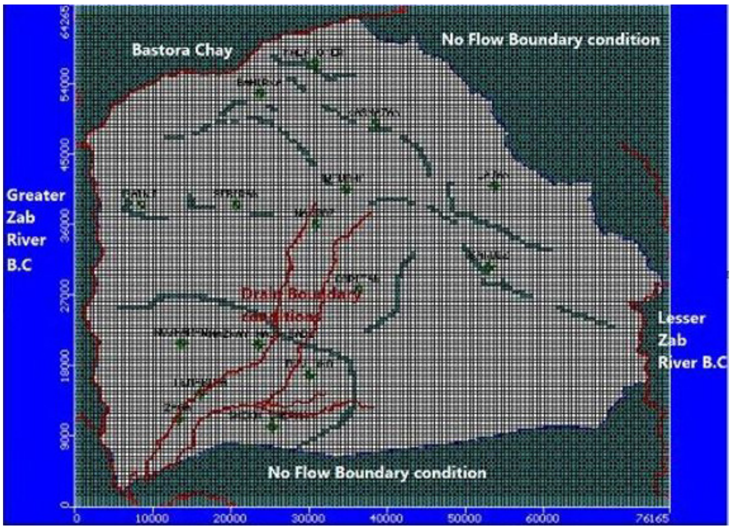


Figure 7. The boundary conditions used in model domain

restriction of flow across these boundaries, mirroring the behavior of a groundwater divide in the actual basin. Additionally, the model incorporates drain boundary conditions in the middle streams of the surface water drainage system. This specific application indicates a nuanced treatment for regions central to surface water drainage, aligning the model's dynamics with the intricate hydrological processes inherent in the Erbil Basin. The integration of these diverse boundary conditions enhances the model's ability to simulate real-world scenarios, contributing to a more accurate representation of the basin's hydrological behavior (Table 4).

Moreover, the the abstraction values and wells data obtained from the actual field data of the wells under operations by directorate of Erbil groundwater. Also, the number and location of the distributed wells within model domain are shown in Figure 8.

Hydraulic properties

The hydrogeological model developed for the Erbil basin integrates essential hydraulic properties, namely hydraulic conductivity (*Kx*, *Ky*, *Kz*), specific yield (*Sy*), and specific storage (*Ss*), as key input parameters. These properties are fundamental to characterizing the subsurface behavior of the aquifer system under study.

In the study of the Erbil Basin, initial parameters are crucial for accurately modeling geological formations and aquifer dynamics. These parameters are derived from extensive data collected through various means, including geological surveys and pumping tests conducted within the study area. By analyzing these data sets, researchers can make informed assumptions about key factors such as aquifer permeability, porosity, and hydraulic conductivity. These initial parameters serve as the foundation for subsequent

Table 4. Rivers and drains boundary conditions input data

River data	River stage (m)	River bed bottom (m)	Conductanc (m^2/day)
Lesser Zab	261.582	259.582	6
	249.693	247.693	6
Greater zab	263.923	261.923	6
	202.933	202.933	6
Bastora Chay	631.5	629.5	6
	284.251	282.251	6
Drain1	383.545	381.545	3441.055
	206.604	204.604	4622.723
Drain2	404.307	402.307	493.947
	223.5	221.5	5602.306
Drain3	299.077	297.077	2286.021
	258.011	256.011	5128.873

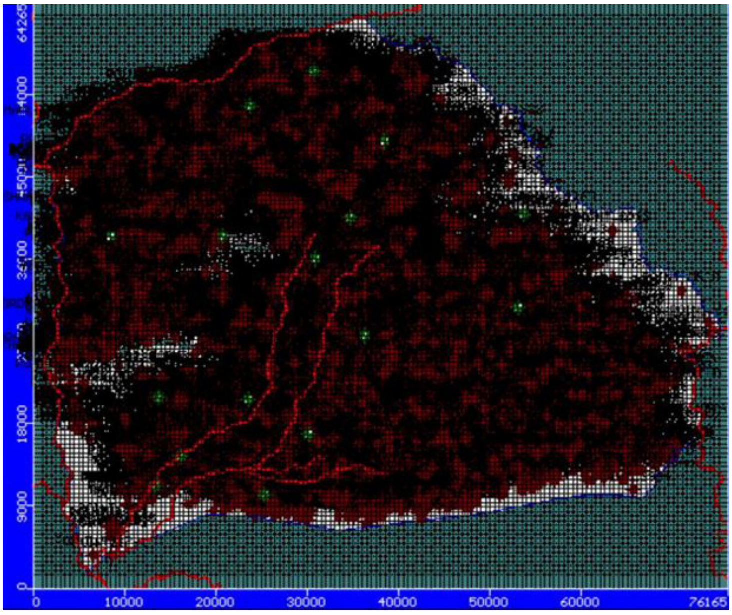


Figure 8. Distribution of the pumping wells within Erbil Basin

hydrogeological modeling, allowing scientists to simulate groundwater flow patterns, assess potential water resource availability, and predict the effects of various extraction or injection scenarios on the aquifer system [39]. Through meticulous calibration and validation processes, these initial parameters are refined and adjusted to enhance the accuracy and reliability of the hydrogeological models, providing valuable insights for sustainable water resource management and decision-making in the Erbil Basin.

In addition, the study summarized previous studies and historical data to setting the values for the model parameters. Also, obtained aquifer parameters for about 90 pumping wells distributed within study region to simulate the actual real conditions of Erbil aquifers. The details are shown in Table 5.

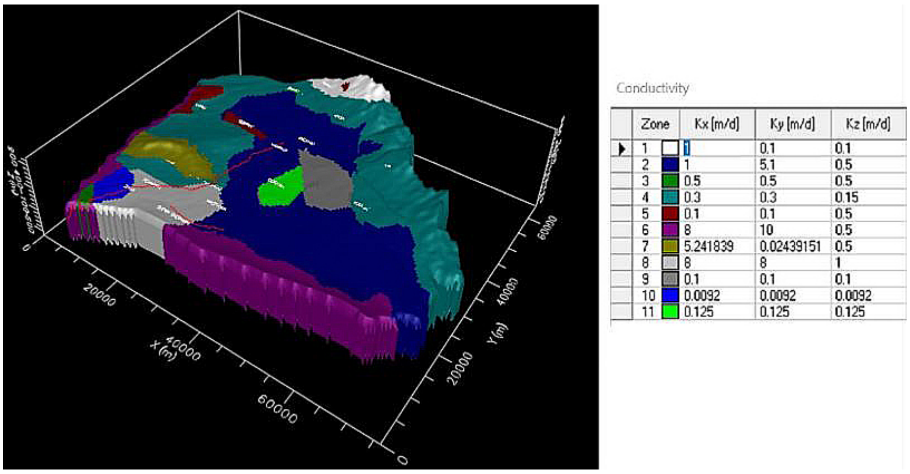
The model strategically divides the model area into eleven distinct zones, aligning with the geological and hydrogeological heterogeneity observed in the real aquifer system of the Erbil Basin. Within each zone, unique values for hydraulic conductivity, specific yield, and specific storage are assigned, reflecting the varying permeability, water-holding capacity, and compressibility of the geological formations. This zonal approach allows for a more realistic representation of the complex hydrogeological conditions across the study area, capturing the spatial variability that exists within the Erbil basin aquifer system. By incorporating these hydraulic properties into the model and accounting for the diverse characteristics of each zone, the simulation aims to provide a nuanced understanding of groundwater flow dynamics, enabling a more accurate representation of the aquifer's response to different stresses and changes in the system over time [31, 33]. In addition, the storage coefficient values were determined such as; the specific yield (Sy = 0.001), the specific storage (Ss = 0.000001 (1/m)), effective porosity (n_e = 0.001) and total porosity (n_{total} = 0.001) and the hydraulic properties of each zones are shown in Figure 9.

These parameters ensure the model's accuracy and reliability in simulating groundwater dynamics because, such as is show in Figure below, it is well simulated the evolution of groundwaters levels versus time, where the highest levels observed match with the highest levels simulated and occur the same with the lowest ones. Also, the calibration/validation of a groundwater dynamics simulation model based on a comparison between observed and simulated groundwater levels over time. The calibration and validation process are crucial for ensuring the accuracy and reliability of the model. If the highest and lowest groundwater levels observed match closely with those simulated by the model, it indicates that the model is effectively capturing the underlying dynamics of the groundwater system.

By ensuring that the observed and simulated data align closely, it demonstrates that the model can effectively predict groundwater behavior under various conditions [33]. These processes help to build confidence in the model's ability

Table 5. The summarized values of the aquifer characteristics of the study results with previous investigation

Description	North (Kapran)	Central	South (Bashtepa)	Total	Reference
Recharge (m^3/yr)	–	–	–	78.08 x 10^6	Parson, 1955 [41]
	94 x 10^6	199 x 10^6	70 x 10^6	363 x 10^6	Haddad, 1974 [42]
	100.01 x 10^6	114.38 x 10^6	73 x 10^6	288.199 x 10^6	Hassan, 1981 [35]
	–	187.32 x 10^6	–	–	Hassan, 1998 [36]
	60.55 x 10^6	–	–	–	Chnaray, 2003 [43]
Recharge (m^3)	–	–	38.17 x 10^3	–	Ahwani, 2008 [37]
Recharge (m/day)	–	0.00024	–	–	Yashooa, 2023 [53]
Recharge (m/day)	–	–	–	0.000157-0.000431	Study result
Hydraulic conductivity (m/day)	–	9	–	–	Hassan, 1998 [36]
	0.12-80.02	–	–	–	Chnaray, 2003 [43]
	–	–	0.3-2.19	–	Shwani, 2008 [37]
	–	0.00025-1.4	–	–	Yashooa, 2023 [53]
Hydraulic conductivity (m/day)	–	–	–	0.0092-10	Study results
Transmissivity (m^2/day)	–	676	–	–	Hassan, 1998 [36]
	16.21-5601.7	–	–	–	Chnaray, 2003 [43]
	–	–	47.44-219.37	–	Shwani, 2008 [37]
Aquifer thickness (m)	–	1829	–	–	Hassan, 1981 [35]
	–	1976	–	–	Haddad, 1974 [42]
Safe yield (m^3/yr)	35.003 x 10^6	51.471 x 10^6	29.998 x 10^6	115 x 10^6	Hassan, 1981 [35]
Effective porosity	–	0.01	–	–	Hassan, 1981 [35]
	–	0.078	–	–	Hassan, 1998 [36]
Effective porosity	–	0.095-0.37	–	–	Yashoo, 2023 [53]
	0.001	0.001	0.001	0.001	Study result



Conductivity

	Zone		Kx [m/d]	Ky [m/d]	Kz [m/d]
▶	1	☐	1	0.1	0.1
	2	■	1	5.1	0.5
	3	■	0.5	0.5	0.5
	4	■	0.3	0.3	0.15
	5	■	0.1	0.1	0.5
	6	■	8	10	0.5
	7	■	5.241839	0.02439151	0.5
	8	■	8	8	1
	9	■	0.1	0.1	0.1
	10	■	0.0092	0.0092	0.0092
	11	■	0.125	0.125	0.125

Figure 9. The hydraulic properties of the model zones

to simulate groundwater dynamics accurately, which is essential for making informed decisions regarding water resource management.

Calibration and validation of the model

Calibration serves as a critical step in refining the accuracy of the hydrogeological model by aligning calculated head values with observed head values [33]. In this study, the calibration process focuses on the time span from 2023 to 2024, utilizing observed head data to iteratively adjust the model through a combination of trial and error. Parameter estimation (PEST) is employed as a method to optimize the model, wherein unknown hydrogeologic parameters are iteratively adjusted to minimize the difference between calculated and observed heads, particularly under steady-state conditions. Subsequently, the model undergoes a one-year simulation from

January 2023 to 2024, capturing transient state conditions. The effectiveness of the calibration is evaluated based on the proximity of computed head values to observed head values. Calibration criteria, including an impressive Correlation coefficient (CC) of 0.997 for calibration and 0.985 for validation, validate the model's accuracy. The standard statistics which are used to evaluate the model calibration process are the standard error of the estimate (SEE) (m), root mean squared error (RMSE) (m), normalized RMSE (%), and the correlation coefficient (CC) (dimensionless). Additional metrics such as mean error (ME), mean absolute error (MAE), and root mean squared error (RMSE) further support the robustness of the calibrated model. Following successful calibration, the model's reliability is assessed through validation, where hydraulic head values from January 2022 to 2024 are compared to the model's predictions, ensuring its applicability beyond the calibration period. Equations used for these statistics are illustrated below Equations (4, 5, 6, 7):

$$SEE = \sqrt{\frac{1}{n(n-1)}}\,\sum_{i=1}^{n}(R_i - R)^2 \tag{4}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} R_i{}^2} \tag{5}$$

$$Normalized\ RMSE = \frac{RMSE}{(X_{Obs})max-(X_{Obs})min} \tag{6}$$

$$CC = \frac{Cov\ (X_{cal}\,, X_{obs}\,)}{(\sigma_{cal}, \sigma_{obs})} \tag{7}$$

where: $R_i = X_{cal} - X_{obs}$,

$$R = \frac{1}{n}\sum_{i=1}^{n} R_i$$

X_{cal} and X_{obs} are the calculated and observed results of a specific parameter, respectively, $Cov(X_{cal}, X_{obs})$ is the covariance between the calculated and observed results, and $(\sigma_{cal} \cdot \sigma_{obs})$ are the standard deviations results of the calculated and observed values of a specific parameter. Formulas of the covariance and standard deviations are illustrated in detail in Visual MODFLOW 2011.1 user's manual designed by Schlumberger Water Services. The obtained results of both calibration and validation process of the model are summarized in Table 6.

Calibration criteria have been considered several statistics parameters that validate the model's accuracy:

- correlation coefficient (CC) of 0.997 for calibration and 0.985 for validation;
- normalized RMS of 2.215% for calibration and 4.68% for validation (SRMS should be low, less than 5% [44];
- mean error (ME) of 1.214 m (a small ME suggests that the overall model fit is not biased) [33];
- for uncertainty checking using obtained CC of 0.989 that means close to one and it is very good calibrated model. The outputs of the Modeling for Erbil basin are in the Figures 11-12.

In addition, the initial stage of calibration involved aligning the calculated groundwater head with observed values by iteratively adjusting permeability parameters through a manual trial-and-error process. This iterative cycle, characterized by adjusting inputs, running simulations, analyzing outputs, and refining inputs, aimed to refine the model's representation of the aquifer's behavior. Given the inherent heterogeneity of the aquifer and the presence of discontinuities such as faults, additional complexity was introduced into the calibration process. Specifically, simulations incorporated non-active cells to mimic these discontinuities, facilitating the replication of challenging connections between distinct aquifer segments. Following successful manual calibration efforts, a more nuanced adjustment phase ensued, employing PEST methodology to fine-tune permeability values for various geological materials. This comprehensive calibration approach ensured that the model accurately reflected the intricate dynamics of the groundwater system, thereby enhancing its reliability for subsequent analyses and predictions.

The inverse modeling approach is commonly employed to determine groundwater aquifer parameters by utilizing observed groundwater head values as dependent variables within the

Table 6. The statistical parameters for error estimation during calibration and validation process

No.	Descriptions	Calibration	Validation
1	Standard Error of the Estimate (m)	2.338	4.975
2	Root Mean Squared (m)	9.137	19.298
3	Normalized RMS (%)	2.215	4.68
4	Correlation Coefficient (CC)	0.997	0.985

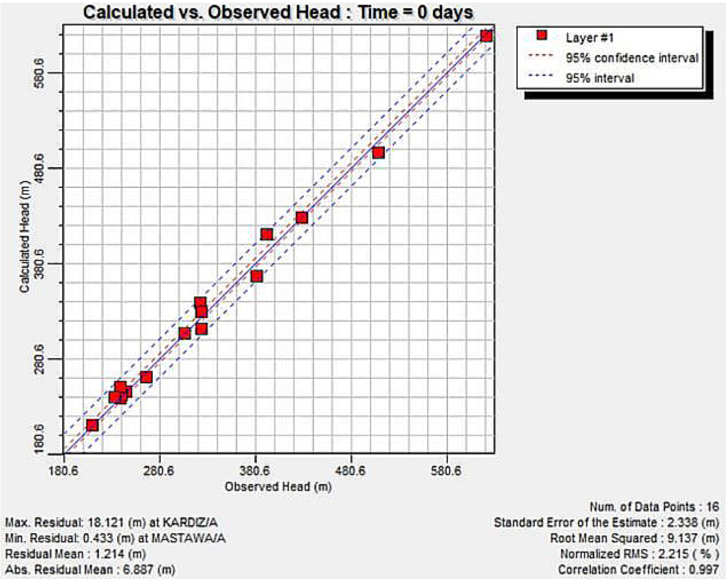


Figure 11. The calculated head versus observed head of calibration

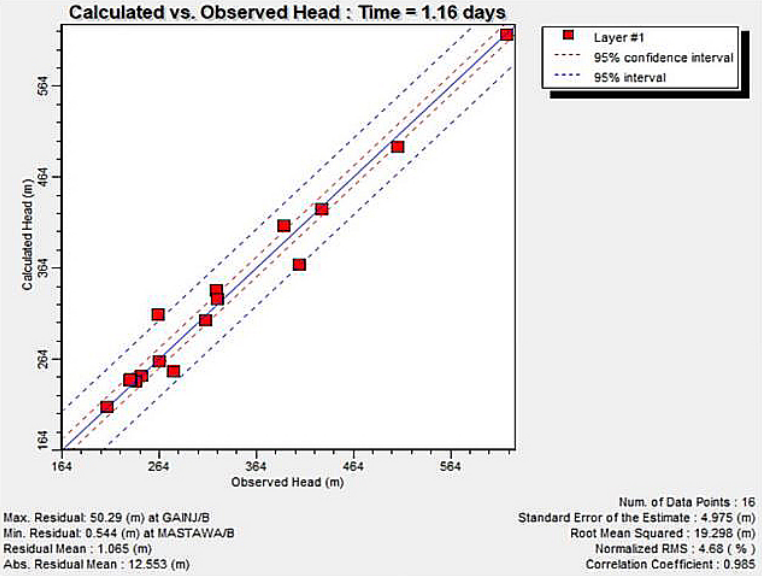


Figure 12. The calculated head versus observed head of validation

governing equation of flow, typically the Laplace equation. Field-measured values of fluxes and heads are often deemed more reliable, establishing a foundation of confidence for the modeling process [33]. A widely advocated method for solving inverse models is the Parameter ESTimation (PEST) technique [45-47]. PEST facilitates the automatic optimization of aquifer hydraulic conductivity through a calibration process. This process aims to minimize the disparity between observed and calculated groundwater heads, with the ultimate objective of achieving convergence, at which point the parameter estimation approach concludes [48]. In the forthcoming section, the parameter estimation approach, integrated within Visual MODFLOW, will be employed to interpolate the hydraulic conductivity of the study site. This approach holds promise for accurately characterizing the hydraulic properties of the aquifer, contributing to a more robust understanding of groundwater dynamics and enhancing the efficacy of groundwater management strategies (Fig. 13).

RESULTS AND DISCUSSIONS

Groundwater head

The application of Visual MODFLOW to simulate groundwater dynamics in the Erbil Basin aquifers over the course of 365 days, during

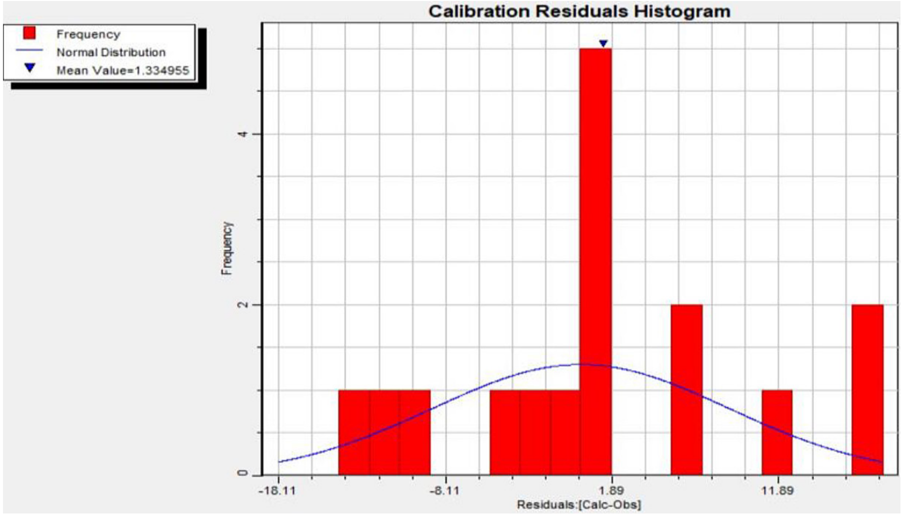


Figure 13. The calibration residual histogram

the years 2023 to 2024, has yielded promising outcomes. The numerical model, calibrated and validated against observed groundwater level data, demonstrates a commendable ability to accurately predict the groundwater head throughout the specified timeframe.

The model successfully captured the intricate interactions within the aquifer system, considering the complexities of hydrogeological parameters, boundary conditions, and potentially varying climatic influences. The calibration process involved fine-tuning model parameters to align simulated groundwater levels with observed data, ensuring a reliable representation of the aquifer behavior which gives ($CC = 0.997$).

Visualization of the model results reveals a comprehensive depiction of temporal variations in groundwater levels. The simulated time series data provides a detailed insight into the dynamic nature of the aquifer, allowing for the identification of seasonal patterns, fluctuations, and potential trends over the specified period and gives ($CC = 0.985$).

Comparisons between simulated and observed groundwater levels affirm the model's predictive accuracy, validating its utility in reproducing real-world hydrogeological conditions. The success of Visual MODFLOW in replicating observed data underscores its effectiveness in simulating the intricate processes governing groundwater flow within the Erbil Basin aquifers. The heads contour lines are shown in Figure 14.

Whereas, for minimizing uncertainties and errors is vital for ensuring the accuracy and reliability of numerical models, particularly in groundwater modeling. Errors can arise from various sources [39]:

- conceptual errors stem from theoretical misconceptions about fundamental processes incorporated into the model.
- numerical errors, on the other hand, originate from equation-solving algorithms, encompassing round-off errors, numerical dispersion, and truncation errors, notably prevalent in transport models.
- inadequacies and uncertainties in input data exacerbate errors, impacting the comprehensive depiction of stresses, aquifer properties, and domain boundaries. Addressing these sources of error is crucial for enhancing the robustness of groundwater models and ensuring their efficacy in practical applications.

Uncertainty in hydrological modeling within the Erbil Basin can be attributed to several factors, with incomplete understanding of the model simulation process and imperfect reproduction of hydrological processes being primary contributors [39]. Inaccuracies in model conceptualization and incomplete input parameters can introduce significant uncertainty into groundwater models. In the context of the Erbil Basin, these uncertainties are particularly pronounced due to challenges in accurately conceptualizing the complex geological formations and aquifer dynamics present in the region. Additionally, inherent natural variability in hydrological processes further complicates modeling efforts, leading to potential discrepancies between simulated and observed outcomes. Addressing these uncertainties requires a comprehensive approach that involves refining model conceptualizations, improving data quality and quantity, and incorporating advanced calibration

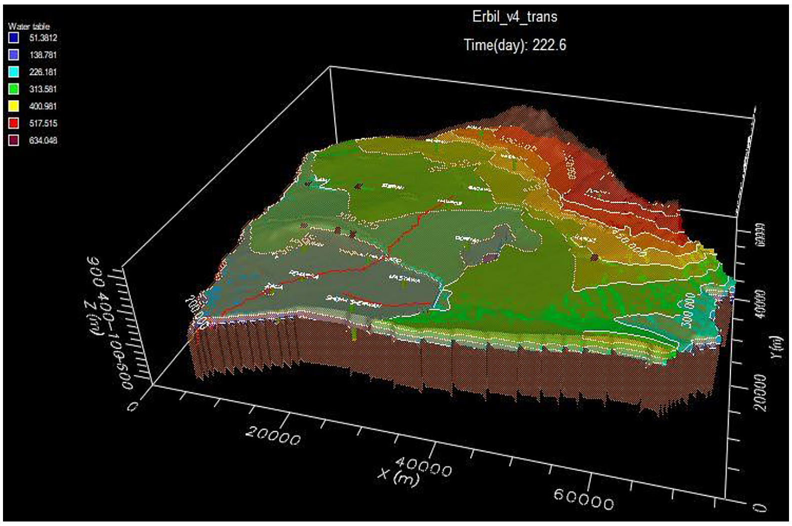


Figure 14. The head contour lines of the Erbil Basin groundwater

and validation techniques to enhance the reliability of groundwater models and support informed decision-making for sustainable water resource management in the Erbil Basin.

For describing a modeling study conducted in the Erbil Basin where different wells within the study area were used to assess the accuracy of the model's predictions. The correlation coefficient of 0.989 suggests a strong agreement between the simulated and observed heads, indicating that the model is performing well in representing the hydrogeological conditions of the basin. However, despite the high correlation coefficient, it's important to recognize that there may still be uncertainties associated with the model. These uncertainties could arise from various sources such as data limitations, simplifications in the model assumptions, or variability in the subsurface conditions that are not fully captured by the model. To further validate the model and reduce uncertainties, it may be beneficial to conduct sensitivity analyses to assess the influence of different parameters or boundary conditions on the model results. Additionally, comparing the model predictions with independent data sources or conducting field measurements to validate the model's predictions can provide further confidence in its accuracy.

Recent research has underscored the critical importance of addressing uncertainties within numerical modeling frameworks, particularly in the context of groundwater flow simulations. Yangxiao and Van Geer (1992) pioneered a stochastic program designed to mitigate and quantify uncertainties inherent in groundwater modeling, focusing on input data utilized by the widely used numerical model MODFLOW. This innovative approach represents a significant advancement in enhancing the reliability of groundwater models by incorporating stochastic methodologies. Building upon this foundation, scholars like [33, 50] have advocated for the integration of numerical and stochastic models. By combining these complementary approaches, researchers aim to more accurately capture uncertainties and improve the overall accuracy of groundwater modeling (Figure 15).

Groundwater flow directions

This study has successfully determined the prevailing groundwater flow direction within the Erbil Basin aquifers. The analysis reveals a consistent and predominant flow pattern originating from the northeast and flowing towards the southwest, ultimately converging towards the Greater Zab sides. This consistent directionality signifies a coherent and well-defined regional flow path that characterizes the broader hydrogeological dynamics within the Erbil Basin, see Figure 16.

Water budget

This study also found the values of water budget results. These results serve as a comprehensive assessment, encapsulating all pertinent input and output parameters within the framework of the model. The water budget, a fundamental aspect of hydrological modeling, entails a meticulous scrutiny of the water inflows and outflows within the basin. Input parameters, including precipitation, runoff, and groundwater recharge, are

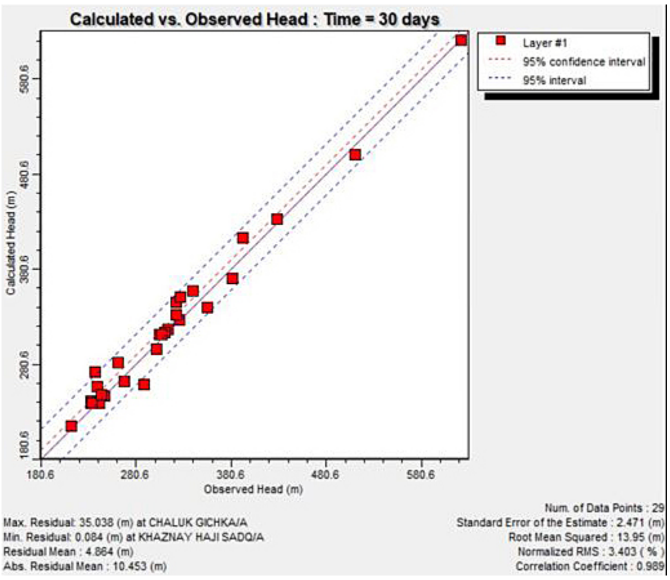


Figure 15. The uncertainty checking observed versus simulated head

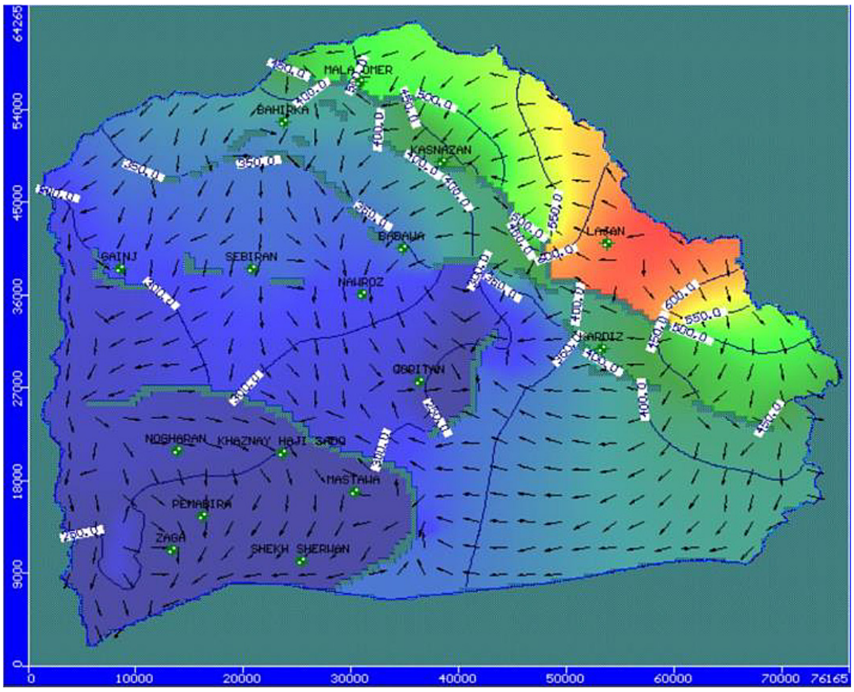


Figure 16. Ground water flow direction in Erbil Basin

examined in conjunction with output parameters such as evaporation, surface runoff, and groundwater discharge. By meticulously quantifying these components, the study aims to provide a holistic understanding of the water dynamics in the Erbil Basin. This detailed water budget analysis not only enhances the model's accuracy and reliability but also offers valuable insights into the sustainability and management of water resources within the basin, thereby contributing to informed decision-making in the realm of water resource planning and conservation.

Furthermore, this study computed the interaction between the rivers and the Erbil groundwater basin, yielding crucial findings for the study area. The observed loss of water by the rivers is a significant revelation, precisely reflecting the arid and semi-arid nature of the region. This insight underscores the delicate balance of water dynamics in the area and emphasizes the need for strategic water resource management practices to address the challenges posed by the arid conditions. However, the interaction between groundwater and surface water systems, such as rivers

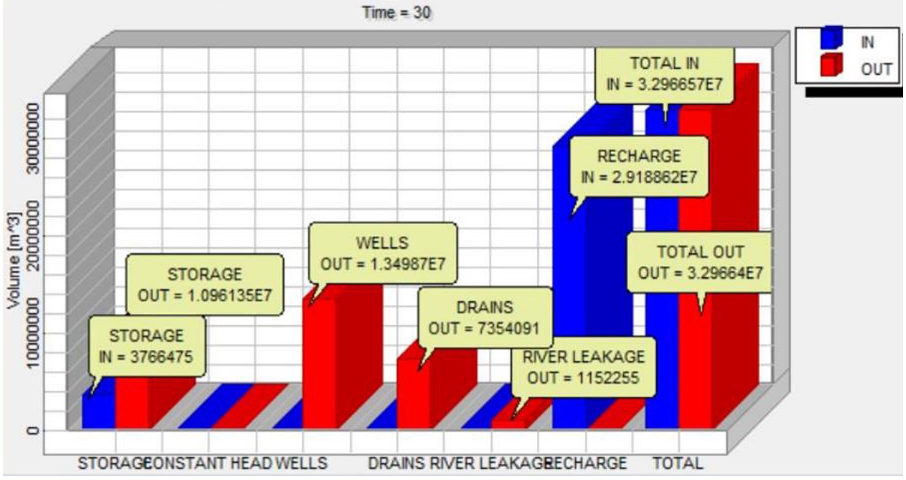


Figure 17. Water budget analysis

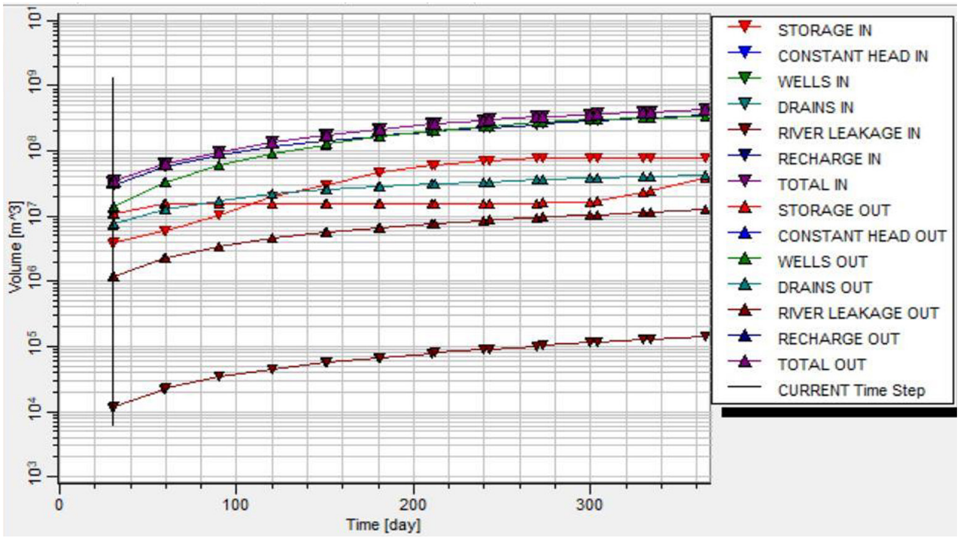
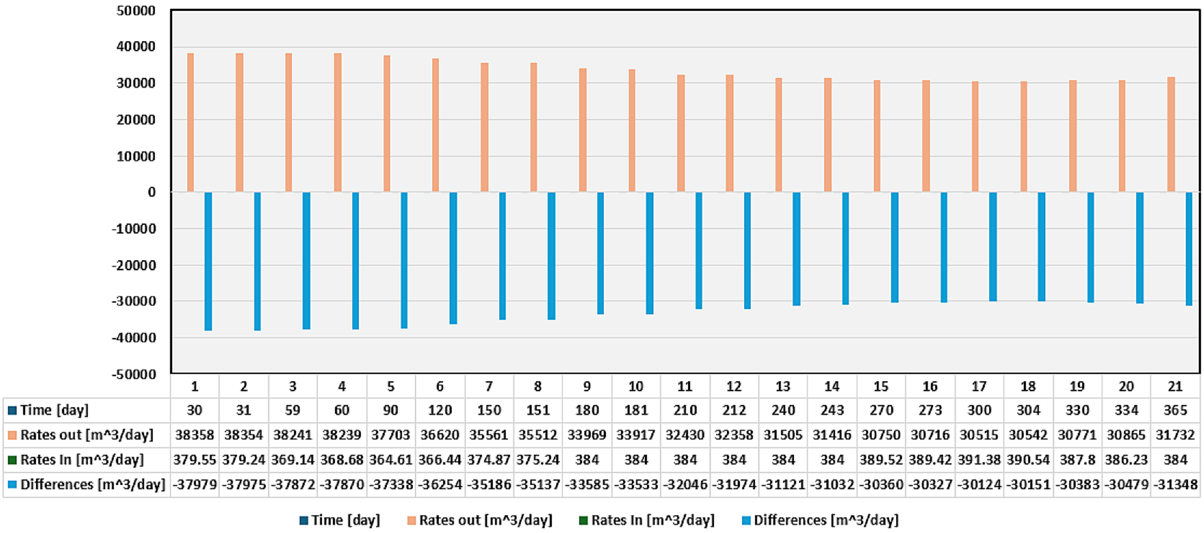


Figure 18. Time series of all variables

or streams, is influenced by the head gradient difference between the groundwater regime and the water level of the river. When the groundwater level is higher than the river water level, groundwater can discharge into the river, replenishing its flow. Conversely, when the river water level is higher than the groundwater level, water from the river can infiltrate into the groundwater system, contributing to groundwater recharge. The River package (RIV) within the Visual MODFLOW program is specifically designed to simulate these flow effects between groundwater and surface water systems. By incorporating parameters such as hydraulic conductivity, river stage, and riverbed conductance, the RIV package allows for accurate representation and modeling of the dynamic interactions between groundwater and surface water bodies, facilitating comprehensive assessments of water resources and hydrological processes within a given area [33,39]. Furthermore, the conductance of the river was calibrated during the model calibration process. This involved adjusting the conductance value to achieve a water table within the river that closely matched the observed water table, thereby enhancing the model's accuracy and reliability in simulating the interaction between the river and the aquifer. Thus, the obtained data from the modeling results are plotted in the Figure 19.

Scenarios for future aspects

Scenario1: reduction of (20%) of the production wells for next 5 years in (2029): the study conducted an in-depth analysis by examining four distinct scenarios to evaluate the potential impacts on groundwater resources and the aquifer system. In scenario 1, the researchers projected



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
■ Time [day]	30	31	59	60	90	120	150	151	180	181	210	212	240	243	270	273	300	304	330	334	365
■ Rates out [m^3/day]	38358	38354	38241	38239	37703	36620	35561	35512	33969	33917	32430	32358	31505	31416	30750	30716	30515	30542	30771	30865	31732
■ Rates In [m^3/day]	379.55	379.24	369.14	368.68	364.61	366.44	374.87	375.24	384	384	384	384	384	384	389.52	389.42	391.38	390.54	387.8	386.23	384
■ Differences [m^3/day]	-37979	-37975	-37872	-37870	-37338	-36254	-35186	-35137	-33585	-33533	-32046	-31974	-31121	-31032	-30360	-30327	-30124	-30151	-30383	-30479	-31348

Figure 19. The difference between river leakages (in-out)

the outcomes over the next five years under the premise that 20% of the existing wells would be decommissioned or become non-functional. This scenario aimed to assess the consequences of a reduction in available wells on groundwater availability and sustainability if the client decided to close wells due to implementing water treatment plants (WTP) (Figures 20-21).

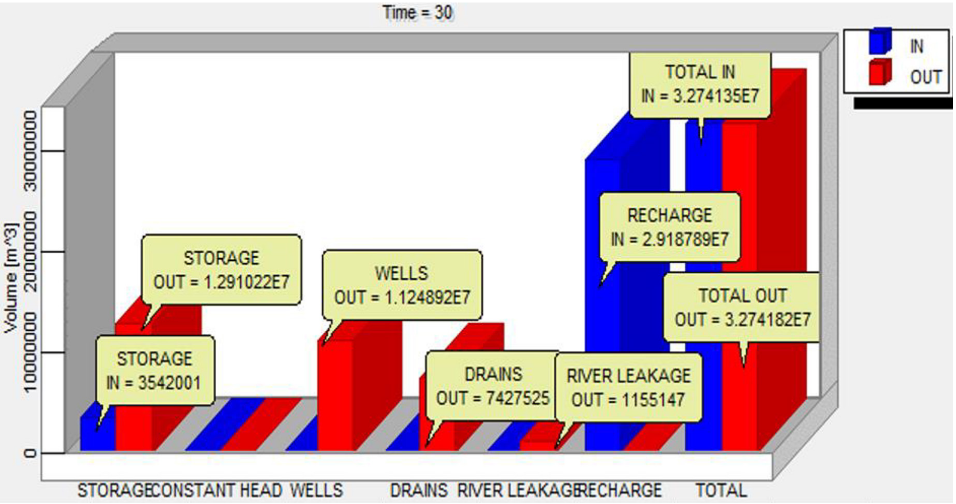


Figure 20. Water budget for scenario 1

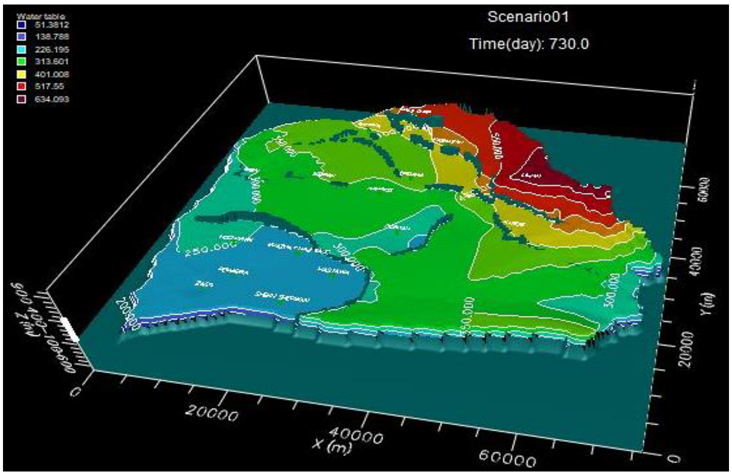


Figure 21. Simulation of head in scenario 1

Scenario 2: implementing two injection wells in Binaslawa and Daratoo locations: in scenario 2, the focus shifted towards exploring the feasibility and effectiveness of utilizing injection wells as a means of replenishing the aquifer and enhancing groundwater recharge rates. By introducing this intervention, the study aimed to simulate the potential benefits and limitations associated with artificial aquifer recharge techniques, thereby offering insights into sustainable water management strategies (Figures 22-23).

Scenario 3: Simulation head in case of removing Bastora river: Scenario 3 delved into a hypothetical situation wherein the primary recharge source, such as a top river, was removed from the hydrological system. This scenario allowed researchers to investigate the repercussions of significant changes in surface water dynamics on groundwater recharge processes and aquifer sustainability, highlighting the interconnectedness of surface water and groundwater resources (Figures 24-25).

Scenario 4: Simulation head for wells dried after next (20) years: scenario 4 projected the long-term implications of continued groundwater extraction by envisioning a future where all wells within the study area would be depleted or rendered non-operational within the next 20 years. This scenario aimed to underscore the urgency of implementing proactive measures to mitigate overexploitation and depletion of groundwater resources, emphasizing the importance of sustainable water management practices and conservation efforts to safeguard future water security (Figures 26-27)

Overall, these scenarios provided valuable insights into the complex dynamics of groundwater systems and offered a comprehensive understanding of potential future scenarios, thereby informing policymakers, stakeholders, and resource managers in making informed decisions to ensure the long-term sustainability of groundwater resources, such as the lack of the

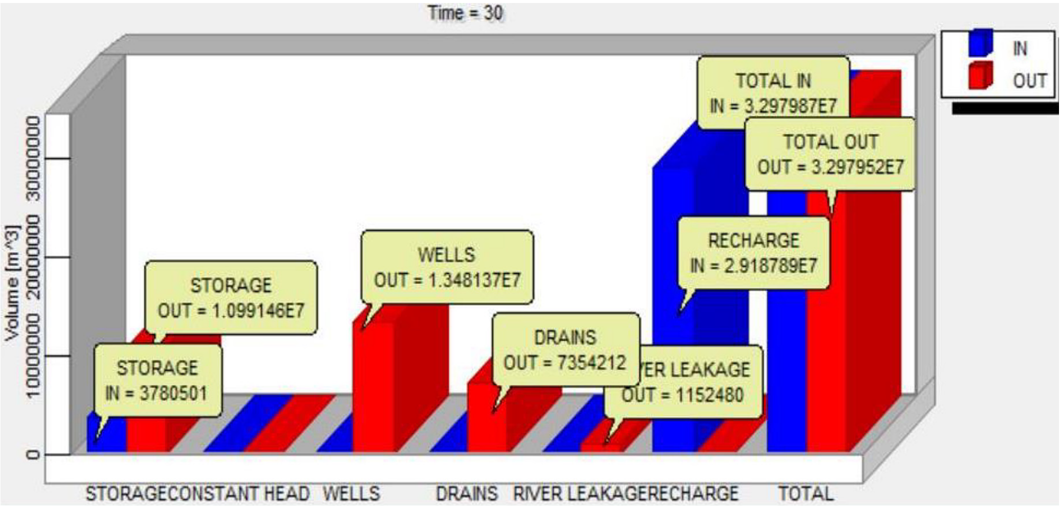


Figure 22. Water budget for scenario 2

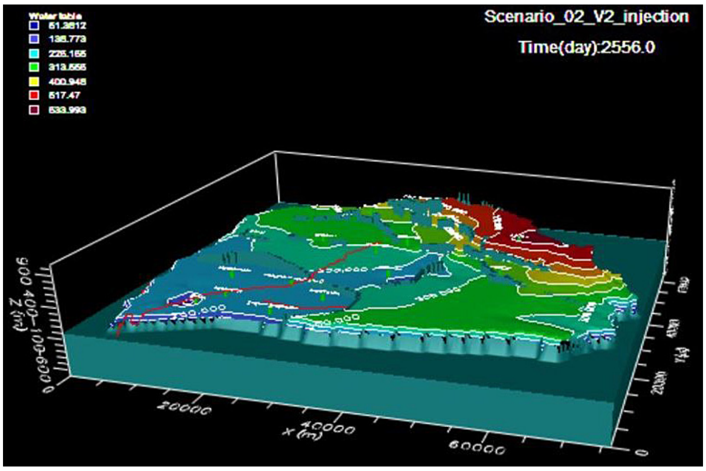


Figure 23. Simulation head for scenario two injection wells

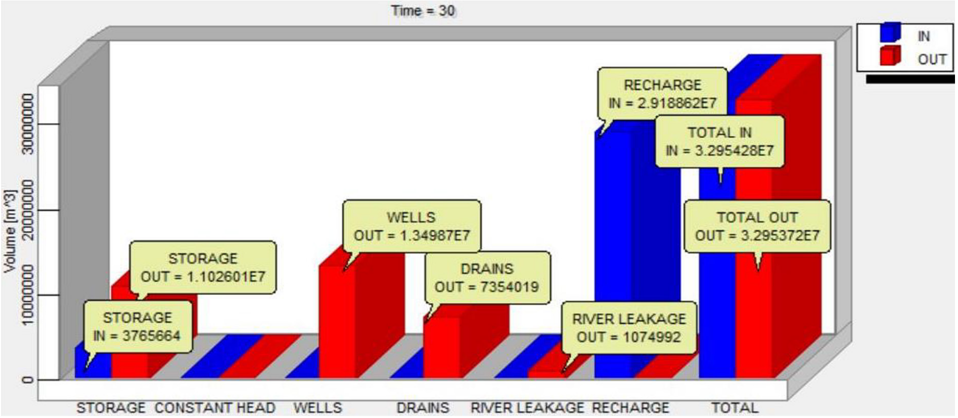


Figure 24. Water budget for scenario 3

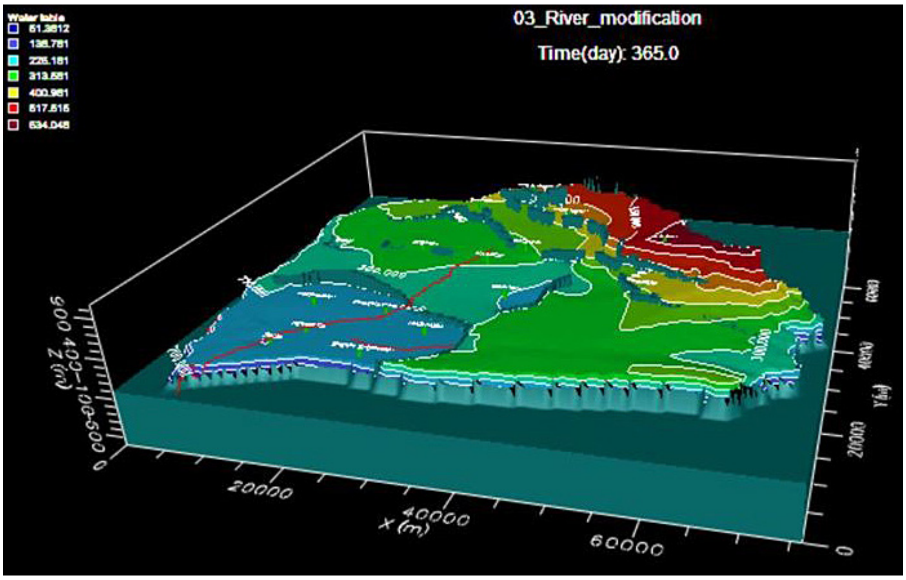


Figure 25. Simulation head of scenario 3

Erbil groundwater resources described the cluster of illegal wells [52, 53].

The groundwater dynamics within the Erbil Basin were comprehensively investigated through a modeling approach facilitated by Visual MODFLOW. The calculated groundwater heads exhibited a significant concurrence with observed heads, as demonstrated by various statistical parameters, attesting to the robustness of the developed model for this study area. The alignment between calculated and observed heads underscores the accuracy achieved in capturing the intricate hydrogeological processes governing the groundwater system in the Erbil basin. Utilizing the PEST tool and trial-and-error methods for estimating aquifer parameters, specifically hydraulic conductivity and specific yield, yielded comparable results, reinforcing the reliability of the model. The negligible disparity in parameter estimation suggests a high degree of consistency and convergence between different methodologies employed in this study. Incorporating uncertainty analysis, the model achieved a remarkable 0.997 correlation coefficient (*CC*) for calibration and 0.985 for validation respectively, signifying a high level of confidence in the model's predictive capabilities. This rigorous evaluation demonstrates the model's reliability in reproducing real-world groundwater behavior and provides a solid foundation for subsequent analyses and applications. The influence of the river system on the Erbil Basin aquifers was evident, with estimated groundwater abstraction reaching 333.0999 Million Cubic Meters (MCM). This significant abstraction has the potential to enhance the aquatic environmental condition by contributing to river baseflow and supporting ecosystem sustainability. However, the study also identified a decline

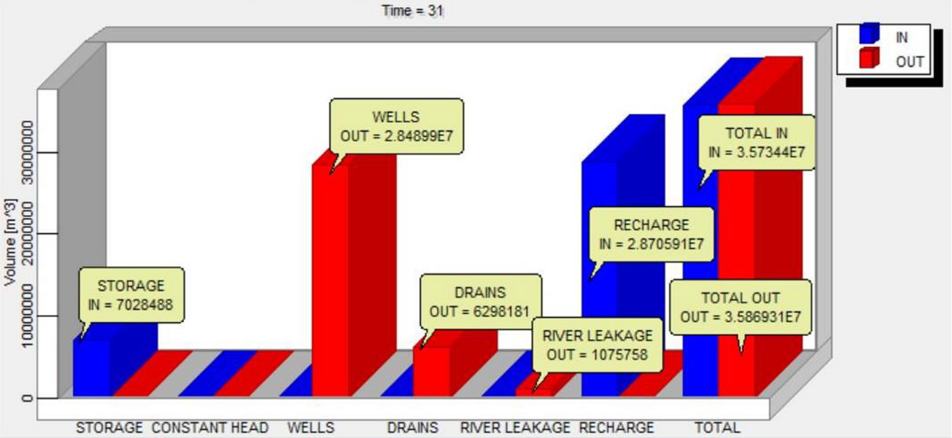


Figure 26. Water budget for scenario 4

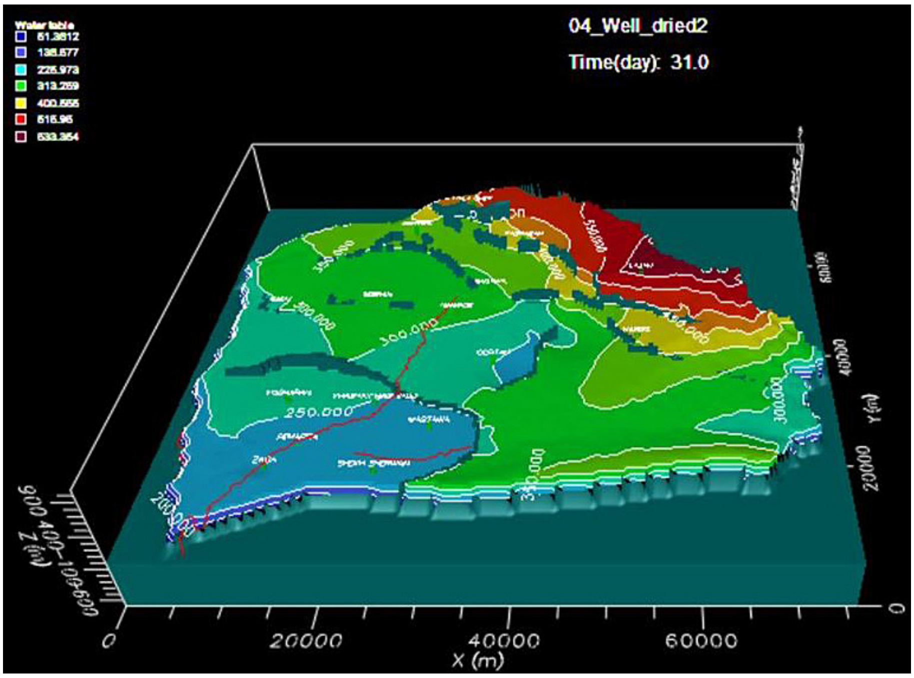


Figure 27. Simulation head of scenario 4

in groundwater levels attributed to excessive extraction for agricultural purposes. This highlights the delicate balance between water resource utilization for economic activities and the preservation of the aquifer's long-term sustainability. Temporal variations in hydraulic head revealed the high sensitivity of the Erbil aquifer to rainfall events, with a rapid response to precipitation. This responsiveness underscores the importance of considering climatic factors in groundwater management strategies, particularly in arid regions where rainfall plays a pivotal role in sustaining aquifer recharge. At the end, the integration of Visual MODFLOW, PEST tool-based parameter estimation, and uncertainty analysis has provided a robust framework for understanding and managing the groundwater dynamics in the Erbil Basin. The identified influences of the river system, groundwater abstraction, and sensitivity to rainfall contribute valuable insights for informed decision-making in water resource management, emphasizing the need for sustainable practices to balance competing demands on the aquifer system.

The study further enhanced its analysis by incorporating uncertainty analysis techniques to validate the accuracy and reliability of the calibrated model. This involved integrating 29 additional observation data points related to groundwater levels into the existing calibrated model. By doing so, researchers aimed to assess the model's performance under varied conditions and ascertain its capability to accurately replicate real-world groundwater dynamics. The results confirmed that the model in good performance because the correlation coefficient is 0.989. Also, the study compared hydraulic characteristics of Erbil basin Aquifer results obtained with previous studies that are within the acceptable ranges as well. In conjunction with uncertainty analysis, the study concurrently developed four distinct scenarios, each representing different hypothetical cases or future conditions. These scenarios were meticulously crafted to explore a range of potential outcomes and impacts on groundwater resources, considering various factors such as changes in water extraction patterns, introduction of artificial recharge methods, alteration of surface water dynamics, and long-term depletion trends. By combining uncertainty analysis with scenario development, the study adopted a robust approach to evaluate the model's predictive capabilities and its ability to simulate diverse hydrological scenarios accurately. This integrated methodology allowed researchers to not only validate the model against observed data but also to anticipate and assess the potential implications of different management strategies and environmental changes on groundwater resources. Through this comprehensive approach, the study provided valuable insights into the uncertainties inherent in groundwater modeling, while also offering a nuanced understanding of how different scenarios could shape the future sustainability and resilience of groundwater systems. This integrated analysis framework serves as a valuable tool for decision-makers and stakeholders tasked with managing and protecting groundwater resources in the face of evolving environmental and anthropogenic pressures.

CONCLUSIONS

In conclusion, the results obtained from the developed model using Visual MODFLOW offer a robust and comprehensive understanding of the groundwater dynamics within the Erbil Basin aquifers. The successful alignment of calculated heads with observed heads, validated by various statistical parameters, signifies the accuracy and reliability of the model. This model not only fills critical knowledge gaps by determining unknown aquifer system parameters such as hydraulic conductivity, specific yield, recharge rates, and groundwater abstraction, but it also sheds light on the intricate influences of the river system. The estimated groundwater abstraction, coupled with insights into the sensitivity of the aquifer to rainfall events, positions this model as a valuable tool for future water resource management in the Erbil Basin. By encapsulating the complex behavior of the aquifer system, the model can serve as a foundation for a basin plan, guiding sustainable practices that balance water resource utilization with the preservation of groundwater resources. This holistic understanding, encompassing all relevant parameters and interactions, contributes to the long-term sustainability of groundwater resources in the selected region, laying the groundwork for informed decision-making and proactive management strategies in the face of evolving water challenges.

Accordingly, this study concluded that the successful construction of a groundwater model for transient conditions plays a pivotal role in the effective management of Erbil basin's groundwater resources. This modeling effort provides a comprehensive understanding of the current state of the aquifers, their interaction with river systems, and the potential impacts of climate change on groundwater dynamics. By accurately representing the complex hydrogeological conditions through tools like Visual MODFLOW, decision-makers gain valuable insights into the flow patterns, recharge areas, and the sustainability of groundwater extraction. A well-calibrated and validated model, as indicated by high correlation coefficients during calibration and validation processes, enhances the reliability of predictions and simulations. This, in turn, allows for informed decision-making in resource allocation, especially in regions where water scarcity is a pressing concern. The model's ability to forecast future scenarios, such as changes in groundwater availability under different climate conditions, enables proactive planning and adaptation strategies. Ultimately, the successfully built groundwater model becomes a crucial tool for sustainable water resource management in the Erbil basin.

Recommendations derived from the model's insights, such as avoiding illegal well drilling and implementing continuous monitoring, contribute to the long-term viability of groundwater resources. This proactive approach ensures that the basin's water needs can be met while minimizing the impact on the aquifers and promoting resilience in the face of evolving environmental conditions. Given the scenario described for the Erbil Basin groundwater, where poor management is leading to the potential drying up of wells within the next 20 years, it's clear that urgent action is needed to address this issue. One recommendation to avoid drilling more wells could be to prioritize the implementation of sustainable groundwater management practices. The following points are some specific steps the government could take:

- implement water conservation measures: encourage and enforce water-saving measures in agriculture, industry, and households to reduce overall water demand;
- promote efficient irrigation techniques: invest in and promote the use of modern irrigation methods such as drip irrigation, which can significantly reduce water consumption in agriculture;
- develop alternative water sources: invest in projects for wastewater treatment and reuse, as well as rainwater harvesting systems, to supplement groundwater resources;
- regulate groundwater extraction: enforce strict regulations on groundwater pumping to prevent overexploitation and depletion of aquifers. Implementing quotas or permits for well drilling can help control extraction rates;
- invest in research and monitoring: allocate resources to better understand the groundwater system through research and monitoring initiatives. This can help inform decision-making and improve management practices;
- public awareness and education: raise awareness among the public about the importance of conserving groundwater resources and the consequences of overuse. Education campaigns can encourage behavioral changes that contribute to water conservation.;
- collaborate with stakeholders: work with local communities, industries, and agricultural stakeholders to develop and implement sustainable water management plans that consider the needs of all parties involved;
- policy and governance reforms: review and update existing water policies and governance structures to ensure they are effective in addressing current challenges and promoting sustainable water management practices;
- by implementing these measures, the government can work towards mitigating the risk of groundwater depletion and ensure the long-term sustainability of water resources in the Erbil Basin. Avoiding the drilling of additional wells is just one aspect of a comprehensive strategy to address the underlying issues contributing to the water scarcity problem.

Acknowledgments

This study is a part of PhD research that implemented in Erbil Basin.

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