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Research Article

SWAT-MODFLOW Model for Groundwater Recharge Variation Assessment: Lower Zab River Basin, Northeastern Iraq

Mohammed Jalel Rahem[1*], Ruqayah Mohammed[2]

[1]Civil Engineering Department, Faculty of Engineering, The University of Babylon, Hilla, Iraq
* **Corresponding Author Email:** moh_82eng@yahoo.com- **ORCID:** 0009-0008-2042-101X

[2]Civil Engineering Department, Faculty of Engineering, The University of Babylon, Hilla, Iraq
Email: r.mohammed1@yahoo.com- **ORCID:** 0000-0002-8485-2467

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Abstract:

For surface and groundwater simulations, recharge is a fundamental water balance unit. Yet, measuring its regional spatiotemporal variation poses a substantial challenge. Mathematical and empirical simulation are the most frequently used approaches at the basin scales. However, the accuracy and dependability of integrated models may be limited due to the limitless number of unknowns and uncertainties they contain. In the Lesser Zab River Basin, A QSWATMOD variant was suggested for evaluating groundwater recharge in northeastern Iraq. The paired version was calibrated using a hydraulic head and daily circulating drift. In comparison to the SWAT version, the QSWATMOD version performed well throughout the flow drift simulation. The results of the study verified that during the predicted period, the watershed saw significant fluctuations in groundwater recharge. The wet season is when a significant amount of recharge takes place. It makes a significant contribution to the region's average yearly precipitation. The water stability components were assessed locally, and the direct waft additives (lateral and surface) demonstrated significant contributions. All things considered, the QSWATMOD model predicted groundwater recharge in the study area with a respectable degree of accuracy.

1. Introduction

Because of the increasing demand for water supplies, climate change, and poor resource management, sustainable development and resource management are essential in watersheds with both agricultural and urban land use [1,2,3,4]. To preserve and oversee the water resources within the watershed, a comprehensive Understanding The hydrological cycle and the system that goes along with it are extremely significant. [5,6]. Watershed recharge-discharge, water quality, and water supply are all impacted [6,7,8]. Accurate estimation of water balance components is also crucial [5,6,9]. Therefore, Assessing groundwater recharge in the reservoir under study is the primary goal of this research project. Many methods, including physical [10,11,12], tracer [13,14,15], and numerical approaches [16,17,9], were used in earlier studies to assess groundwater recharge. When evaluating recharging, each approach has drawbacks [11]. More and more researchers are using the numerical method to measure groundwater recharge, which entails examining aquifer and surface conditions or both. [18,19].

The MODFLOW model is commonly used to analyze unconfined groundwater flow, whereas surface water flow is often simulated using the SWAT model. SWAT is widely used across various catchment scales to assess surface and groundwater quality and quantity and to forecast the impacts of specific catchments on land use/cover and climate change.

While SWAT focuses on surface processes, its aggregated nature limits its ability to model groundwater flow. Several tactics have been carried out to cope with the original SWAT groundwater module's shortcomings. Alternatively, the MODFLOW model, with its distributed and physically primarily based method, is a good option for modeling groundwater flow considering various boundary situations. However, it's far inadequate for modeling floor water float. The coupled QSWATMOD approach is essential for resolving the issues of those fashions and offering a greater correct depiction of the hydrological device.

The integration of SWAT and MODFLOW fashions was first of all delivered through Sophocleous et al. [20] and has considering that been enhanced through version overall performance comparisons with the SWAT version [18,21]. Bailey et al.' integrated model framework uses the SWAT model to model surface hydrological approaches. [22] developed. Newton-Raphson formulation for MODFLOW, or MODFLOW-NWT [23], which also can address unconfined aquifer subsurface water flow problems, is utilized to simulate groundwater flow processes. Previous studies using the QSWATMOD model, as described by Wang and Chen [24], are divided into two categories: situational and non-situational simulations. Although QSWATMOD situational scenario simulation studies consider how groundwater abstraction affects surface water resources [25], Simulations of water flow, groundwater discharge, surface-regional water balance, and groundwater interaction are the main areas of interest for non-situational investigations. [18,21,22]. According to Ntona et al. [26], QSWATMOD has been widely used as a model for analyzing surface–groundwater interactions worldwide from 1992 to 2020 and remains essential in current research. In Africa's Limpopo River Basin, for example, Mosase et al. [27] used QSWATMOD to estimate the water table level, surface and subsurface water interaction, and the spatiotemporal distribution of recharge. Additionally, Sophocleous and Perkins [28] employed QSWATMOD to explore the impacts of water abstraction on water table levels and streamflow in three basins in Kansas, USA, while also analyzing various scenarios, including how water resources are affected by climate change. Gao et al. [21] used an integrated model to assess the spatiotemporal variations of surface water resources in a U.S. River catchment. Additionally, Taye Samiromi and Koush [18] investigated the relationship between surface and groundwater in Iranian agricultural watersheds using the integrated model highlighting the fact that the primary cause of water scarcity in the study area is excessive groundwater use, not just climate change. Chunn et al. [29] evaluated the effects of groundwater abstractions and climate change on the groundwater-surface water relationship in western Canada using the same model. Highlighting the important role that groundwater misuse plays in lowering groundwater levels and river flow, as mentioned by [18,30]. To lower the uncertainty associated with parameter calibration, The QSWATMOD model has been subjected to parametrization tools. in recent hydrological investigations [31, 32]. In the northern Danish Ogerby River Basin, [31] employed the approach of a standardization technique for a coupled model to assess how water flow responded to groundwater withdrawal. An important benefit of QSWATMOD is its ability to simulate coupled surface-groundwater scenarios. And has demonstrated high precision in streamflow evaluation [25,31,22]. However, like other numerical models, QSWATMOD is subject to uncertainty [33], particularly in regional-scale environmental models, which frequently experience a great deal of uncertainty because of many unknown factors, with water table fluctuation (WTF) being one of the most direct, precise, and uncomplicated approaches [11,34,35,36]. This approach depends on aquifer parameters, which can be ascertained in a variety of ways, and observed groundwater level data series [11,35,37]. Enhancements have been made to boost efficiency and decrease subjectivity [38,39]. Chung et al. [40] investigated the recharge of the groundwater reservoir in South Korea. One technique for integrated modeling is to connect a hydrological model, such as SWAT, with the WTF method as a model in Jeju Island. Using the SWAT model in combination with TWTFM. Since it guarantees accurate results, it is advised to consider an alternate method for predicting groundwater recharge [35,36,41]. We use the QSWATMOD model to evaluate groundwater recharge in our study area. To the best of our knowledge, no previous study has evaluated groundwater recharge using a coupled model; this study will be the first to do so.

Such as parameterization choices, input databases, and model structure [24]. For example, during the wet season, a big recharge value is transferred to MODFLOW by the surface water model (SWAT), according to Guevara-Ochoa et al. [34]. Due to the absence of a module in QSWATMOD to account for the interaction between groundwater and soil saturation. While various techniques are used for estimating recharge, the water Another strategy that is suggested is the table fluctuation method.

Estimating groundwater recharge involves various methods,

The present study aims to put forward quantitative and observational techniques for assessing groundwater replenishment's spatial and temporal pattern. Using the QSWATMOD model, the research basin assesses the temporal and spatial distribution of groundwater recharge. This study also presents the seasonal fluctuations in groundwater recharge in the area. Additionally, it acquires and discusses the water balance components.

2. Materials and methods

2.1. Basin description

Between latitudes 43° 21′ 41" and 46º 17′ 55" N and 35° 1′ 29" and 36º 54′ 41" E is where the Lower Zab Basin is located. According to Figure 1, the Lower Zab River's smaller portion is in Iran while its greater portion is in northeastern Iraq. The entire basin extent is 19700.845 Km2, 74.77% is placed inside Iraq which is 14729.690 km2 and 25.23 % is placed inside Iran which is 4970.310 km2. The topographic characteristics of the study area, such as elevation accurate to 30 meters and the specific SRTM type, were acquired from the USGS (US Geological Survey) (http://earthexplorer.usgs.gov). Subsequently, using the ARC-GIS application, the surrounding areas were eliminated, and the final representation validating the watershed's geometry was created, as depicted in Figure 1. The Lesser Zab River serves as the primary tributary of the Tigris River. In the Iraqi portion of the basin, the largest dam is the Dokan Dam (35°57'14" N and 44°57'10" E), while Iran is currently constructing one dam and planning to build two more [42].

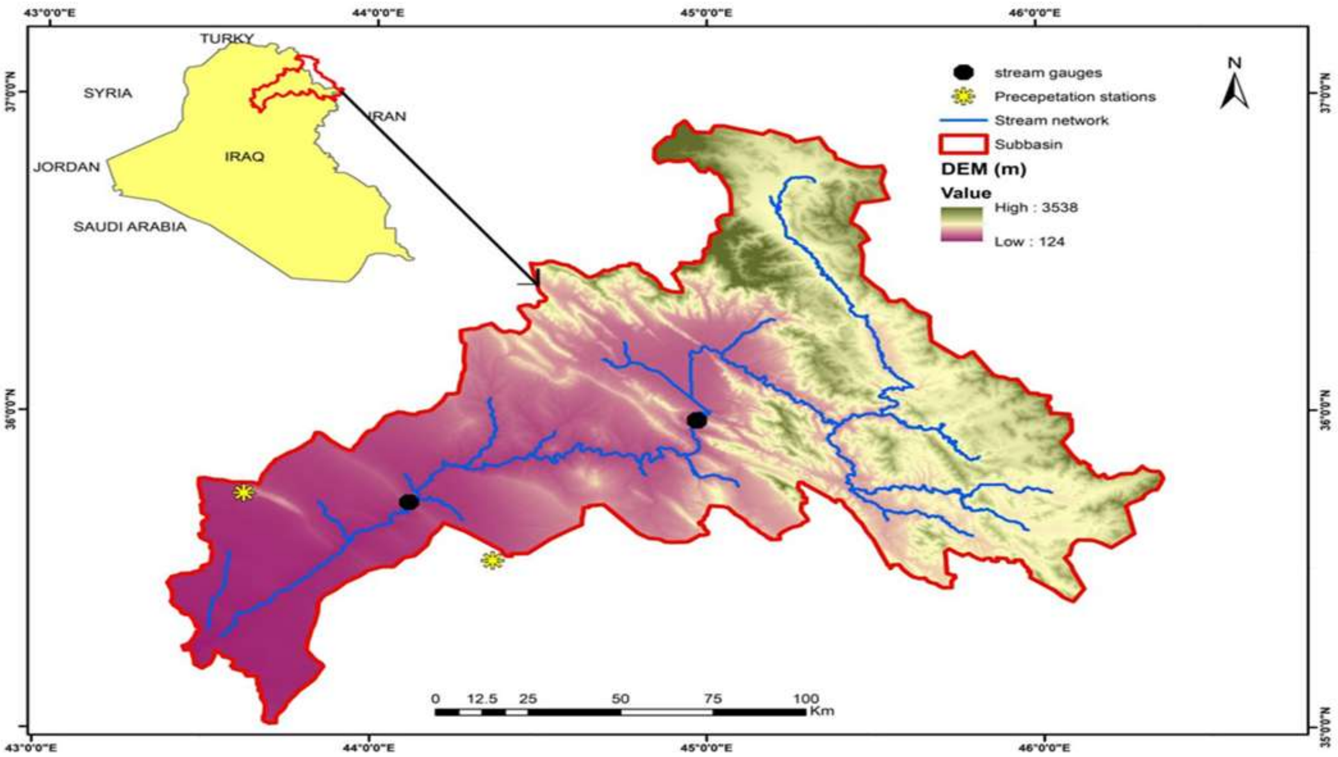

***Figure 1**. Description of the study area: flow network, digital elevation model (DEM), flow gauges, weather station, and rainfall station*

The primary water sources for the stream include rainwater, snowmelt, and various springs, resulting in great discharge rates in the spring period and lower rates in the summer. The weather within the basin differs, ranging from semi-arid conditions in the northern and northeastern regions to arid climates in the southern and southwestern areas. The LZR exhibits the lowest, average, and highest discharges of 6, 227, and 3,420 m³/s, in that order [43]. The basin traverses a range of geological, environmental, and climatic areas. The upper and lower regions of the catchment are predominantly categorized by a mix of different rock types with various lithological characteristics and more easily eroded clastic rocks, respectively. Annual rainfall along the river differs considerably variation, ranging from less than 20 cm at its Iraqi Tigris River confluence to more than 1000 mm in Iran's Zagros region. With annual average air temperatures ranging from 14.5°C to 18.5°C, average temperatures show a similar gradient. Numerous unique lithostratigraphic units, ranging from the Precambrian to the present, can be found in the LZB, including sedimentary, metamorphic, igneous, and Quaternary deposits. The landforms in the catchment show significant topographic variances that affect the moisture content and soil chemistry. The land use and land cover within the LZB mainly consist of bare lands and flooded vegetation, with bare lands accounting for approximately 70% of the total area and flooded vegetation comprising about 15%. The remaining 15% includes crops, water bodies, trees, and areas designated for agriculture. The SWAT model classified the land use into eight distinct categories, as demonstrated in Figure 2.

2.2. SWAT-MODFLOW model

Due to its aggregated nature, the SWAT model is limited in its ability to address groundwater flow, and MODFLOW finds it challenging to estimate surface water conditions (Figure 2).

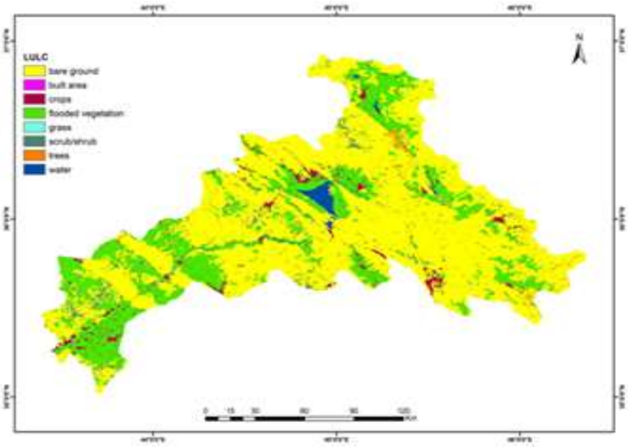

Figure 2. *The lower Zab River Basin land use and land cover (LULC) classification*

Because the groundwater model does not have a land surface hydrology model, the lower Zab River Basin land use and land cover (LULC) classification must be used. To get around these restrictions, the integrated QSWATMOD model substitutes MODFLOW for the SWAT model module for groundwater [24,29]. Data from other models must be transferred for the QSWATMOD model to calculate groundwater recharge accurately. It has been possible to transfer data between individual models by using a mapping scheme Model-simulated deep percolation (HRUs) are used as recharge to the detailed HRUs (DHRUs) in MODFLOW for each grid cell, whereas MODFLOW is used to obtain groundwater discharge in each sub-basin in the SWAT model. [22]. The SWAT model models groundwater recharge, or deep percolation, using Equation 1.

$$\omega_{\mathrm{rchrg},i} = \left(1 - \exp\left[{}^{-1}/_{\delta_{gw}}\right]\right) \cdot \omega_{seep} + \exp\left[{}^{-1}/_{\delta_{gw}}\right] \cdot \omega_{rchrg,i-1} \qquad (1)$$

On the day I, the total amount of water that leaves the soil profile is represented by ωrchrg,i (mm), and the total amount of water that recharges the aquifers is represented by ω_seep (mm). The amount of water that recharges the aquifers on day I-1 is represented by rchrg,i-1 (mm), The groundwater materials' transit time is depicted by δ_gw (days). Using Equation (2), MODFLOW represents groundwater flow utilizing a finite difference method. MODFLOW discretizes the aquifer into layers, rows, and columns. Models simulate groundwater heads down to the grid cell level. Once QSWATMOD has been configured, for recharging scenarios, the MODFLOW groundwater flow equation will be utilized and the groundwater SWAT module will be turned off.

$$\frac{\partial}{\partial x}\cdot\left(K_{xx}\cdot\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\cdot\left(K_{yy}\cdot\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\cdot\left(K_{zz}\cdot\frac{\partial h}{\partial z}\right) - W = S_S \cdot \frac{\partial}{\partial t} \qquad (2)$$

The hydraulic head (h) is measured in meters. The hydraulic conductivity along the x, y, and z directions is denoted by Kxx, Kyy, and Kzz, respectively, and is measured in meters per day. Ss represents the dimensionless specific storage of the aquifer, t (measured in days) denotes time, and W (measured in days) indicates the source or sink. A positive W value signifies. In contrast, a negative value denotes abstraction. Recharge into the aquifer.

2.3. Configuring and linking models

The SWAT model

The research area was constructed using SWAT (version 2012). The SWAT model operates on a daily time series and is semi-distributed. Watersheds and sub-watersheds (sub-basins) were established through the use of a digital elevation model (DEM). Hydrological Response Units (HRUs) are conceptual units that have been used to divide the landscape for this model. An area with comparable soil, land use, slope, and management features is designated as a piece HRU. The SWAT model uses conceptual units (HRUs) to simulate the amount and quality of water resources [44]. A crucial first step is determining the appropriate number of HRUs to modify the model size without omitting critical information [45]. The SWAT model's various HRU definition options allow users to depict the study watershed's heterogeneity in LULC, soil types, and topography. QSWAT is a graphical user interface (QSWAT3, version 1.7.1) utilized to build and execute the study watershed's SWAT model. With a digital elevation model (DEM) of 30 m resolution, the area was contoured and separated into 37 sub-basins (Figure 3). To replicate the water network of the research area, a network of streams was created. After that, 74 HRUs with various HRU choices were created. For this study, a station gauge called Dokan (Figure 1) was used to calibrate streamflow. The model was updated with imported weather data. From 1997 to 2020, The first three years (1998–2000) of the simulation of a SWAT model were known as the "warm-up period," during which the model was unable to produce data that could be interpreted.

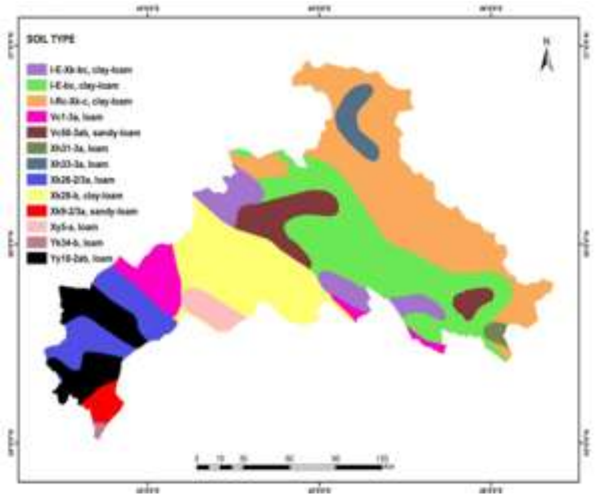

Figure 3. *The lower Zab River Basin hydrological soil types*

MODFLOW model

The GMS software MODFLOW, version 10.4.64, was utilized to develop the conceptual model of the study region. A finite difference method is used in MODFLOW to analyze the groundwater flow in the aquifer in three dimensions [46]. The MODFLOW-NWT (Newtonian Solver) engine was employed in this study to account for variations in the grid cells' confinement and wetness over time. In an unconfined aquifer, MODFLOWNWT can replicate Without rendering the cell hydraulic heads neutral, drying them out., which makes it superior to other MODFLOW versions [24]. We also looked at an upstream weighting (UPW) package that gives dry cells zero magnitudes to compute the head from the intake to the dry cells and to flow out. All things considered; the MODFLOW-NWT run provides a more accurate estimate of the watershed's subsurface water flow [24]. 3259 active grid cells have been identified within the Lower Zab River watershed, which, at a lateral resolution of 2959 m by 2317 m, spans 19700.4 km2. After importing the stream network established during the SWAT delineation procedure as a shapefile into MODFLOW, the driver package was used to create 293 stream cells for the watershed. The DEM raster file and SWAT model provide conceptual top elevation data. About 300 meters below the surface was the lowest elevation.

Sources and sinks, beginning head, river conductance, and hydraulic conductivity are important factors in the modeling of groundwater flow in a steady state. The SWAT percolation output was used to calculate the recharge rate, producing a single MODFLOW number. Thirty monitoring wells data sets from the research region were interpolated to get the initial head values. Similarly, an interpolation method was used to determine the initial values for hydraulic conductivity. As expected, the first simulation showed differences between calculated and observed head values. To address this, the parameter estimation (PEST) algorithm was employed to calibrate the conceptual model. It meant establishing additional pilot sites where there was little data. The minimum and maximum hydraulic conductivity are given identical values. During the calibration procedure, the pilot points were determined. Following the steady-state simulation, the computed and observed heads showed results that made sense, and the transient-state simulation was set up. Before starting the process of coupling SWAT and MODFLOW, the transient simulation was set up with specific yield and specific storage.

SWAT-MODFLOW model integration

Bailey et al. [22] presented the connecting code, a monthly time-step combination of the MODFLOW and SWAT models. A crucial step in integrating Decomposed Hydrological Response Units (DHRUs) is created by converting SWAT Hydrological Response Units (DHRUs). When combined with a MODFLOW grid shapefile, gives the model reliable spatial information. The meshing strategy can be useful because it enables models to exchange their calculated outcomes. Wanting to import or alter the information entered. Park et al.'s procedure indicates the full process of creating and transferring existing mesh files and model integration. [44]. QSWATMOD, a graphical user interface built on top of QGIS, was used in this study. For the coupled model before, during, and after processing, Its Python code makes it ideal for creating linkage files between MODFLOW and SWAT.

Bailey and associates. [22] describe the basic processes. QSWATMOD requires a few key inputs to integrate models.

These include the SWAT output file, shapefiles for subbasins, hydrological response units (HRUs), and the network of rivers.

Additionally, a MODFLOW model folder in native text format is necessary as part of the preprocessing phase.

The MODFLOW and SWAT models are two options for stream networks;

the SWAT stream was utilized. MODFLOW grid cells were paired with the appropriate hydrological response units (DHRUs) to link the models.

Before the coupling process, the QSWATMOD integration was calibrated using a zonal polygon for the MODFLOW model's aquifer parameters.

A single working directory contained all the integrated model files in an orderly fashion.

2.4. Calibration and assessment of model performance

Calibration of SWAT

Observed streamflow data can be used to assess the SWAT model's suitability for streamflow simulation. It is necessary to adjust the parameters that affect the simulated streamflow until they match the real streamflow values. All sources of uncertainty regarding the model, parameters, and input data were taken into account by the Sequential Uncertainty Fitting program (SUFI-2) algorithm. Was used in conjunction with the SWAT-CUP program to accomplish Blöschl and Sivapalan [47]. Jafari et al. [48] provided a thorough explanation of SUFI-2 and other algorithms. This study used a 20-year simulation of the SWAT model., with 2001–2005 serving as the calibration period and 2006–2008 as the validation period. The monthly time series in our investigation provided both a validation and calibration for the streamflow that was observed.

Sensitive parameters were selected from several SWAT hydrological parameters in order to calibrate the model by offering a value within an acceptable range. Evaporation, groundwater, surface runoff, and simulated soil water are all controlled by certain factors. Figure 4 provides comprehensive explanations of a few chosen factors. The model's performance during calibration can be assessed using statistical measures like the regression coefficient (R2) Nash-Sutcliffe efficiency (NSE) and its values (https://mountainscholar.org/bitstream/). The NSE value should be higher than 0.4–0.6 for the calibration procedure. The closer the NSE is to one, the more the model outputs resemble the observed data. The degree to which the observed and simulated data match is assessed using the regression coefficient (R2). NSE was chosen as the study's objective function to determine the simulation through the SWATCUP program's calibration and validation phase. Two stream gauges (Dokan and Dibbis) are part of the study watershed. as indicated in Table 1. Due to missing data from the other stream gauge, which makes it challenging to choose, calibration was done at Dokan. [49].

Calibration of SWAT-MODFLOW models

Model parameters are changed during the QSWATMOD model calibration process to guarantee that the simulated outcomes closely match the observed data. This procedure is essential because it improves the model's predictions for surface and groundwater flows in terms of accuracy and dependability. A thorough simulation of the hydrological cycle is made possible by the combination of MODFLOW (Modular Finite-Difference Groundwater Flow Model) and SWAT (Soil and Water Assessment Tool). SWAT primarily deals with surface water flow, while MODFLOW focuses on groundwater flow. The study overcomes the drawbacks of applying each model independently by integrating them.

During calibration, specific parameters related to land use, soil properties, and aquifer characteristics are adjusted. Statistical measures like the correlation coefficient, root mean square error, and Nash-Sutcliffe efficiency are frequently used to evaluate the objective, which is to minimize the difference between simulated and observed data. The successful calibration of the coupled QSWATMOD model results in improved

Table 1. *Fit and range value details for the SWAT model calibration parameters*

Factors	**Explanation**	Calibrated **Value**	**Range value**
r_CN2.mgt	Wet condition II initial SCS runoff curve number	0.154	-0.2 − 0.2
v_ALPHA.BF.gw	Alpha factor of baseflow (days)	0.39	0 − 1
v_GW_DELAY.gw	Groundwater delay (days)	2.47	1 − 45
v_GWQMN.gw	Water depth threshold for "revap" to occur in the shallow aquifer (mm)	0.061	-0.1 − 0.1
v_GW_REVAP.gw	Groundwater "revap" coefficient	0.05	0.01 − 0.09
v_ESCO.hru	Soil evaporation compensation factor (-)	0.975	0.0 − 1
r_SOL_AWC.sol	The soil layer's available water capacity (mm mm^{-1})	0.126	-0.2 − 0.2

performance compared to using the SWAT model alone. Understanding water balance and managing water resources in the watershed depend on more precise estimates of groundwater recharge, which this improved model offers. Five additional SWAT parameters were chosen for recalibration to enhance streamflow simulation. The aquifer's HK, SS, and Sy parameters were taken into account during the QSWATMOD calibration procedures. Table 2 lists the calibration parameters that were selected and the ranges of values that correspond to them.

Table 2. *Descriptions and value ranges of the calibration parameters chosen by SWAT-MODFLOW.*

Factor	Value Range	Explanation
ALPHA_BF	0.01-0.2	SWAT, Baseflow alpha factor (days)
CH_k2	1-50	Effective hydraulic conductivity of the main channel (mm/h), SWAT
CN2	0.01-1	First SCS runoff curve number for SWAT and moisture condition II
EPCO	0.01-1	SWAT and the plant uptake compensation factor (-)
ESCO	0.01-1	Compensation factor for soil evaporation (-), SWAT aquifer hydraulic conductivity (m/day), MODFLOW specific yield (-), MODFLOW specific storage (m-1), and MODFLOW
Hk	0.1-100	SWAT, Baseflow alpha factor (days)
Ss	0.000001-0.005	Effective hydraulic conductivity of the main channel (mm/h), SWAT
Sy	0.0001-0.4	First SCS runoff curve number for SWAT and moisture condition II

3. Results and discussion

3.1. Calibrated parameters

In the following section, the final automated parameters used in the integrated QSWATMOD model are explained. The values of the calibration parameters in Table 1 are substantially greater than those in Table 3. This difference can be explained by the modification made to account for the simulated streamflow's lower base flow and peak flow conditions. To fine-tune aquifer characteristics before the coupling process, zonal polygons were created based on the hydraulic head distribution [49,50]. A visual depiction of the final automated aquifer parameter value ranges in the study area is shown in Figure 5. The range of the calibrated hydraulic conductivity values is 0.54 to 15.2 meters per day.

Specific yields and storage values, respectively, range from 0.00076 to 0.33 and 0.000001 m-1 to 0.0037 m-1 for the study. Figure 5 shows the apparent relationship between the different aquifer characteristics. Interestingly, after calibrating the study watershed's hydraulic head, it shows an inverse relationship between specific yield and specific storage. A comparison of monthly streamflow for the SWAT and integrated models using simulated and measured data is shown in Figure 5. The streamflow was calibrated between 2001 and 2005 and then validated between 2006 and 2008. Table 4 summarizes model performance data for the SWAT and QSWATMOD models for NSE and R2 between streamflow calculations and measurements.

Table 3. *The final SWAT-MODFLOW calibrated parameter value*

Factor	Value Range	Explanation
ALPHA_BF	0.05	SWAT, Baseflow alpha factor (days)
CH_k2	20	Effective hydraulic conductivity of the main channel (mm/h), SWAT
CN2	0.1	First SCS runoff curve number for SWAT and moisture condition II
EPCO	0.02	SWAT and the plant uptake compensation factor (-)
ESCO	0.02	Compensation factor for soil evaporation (-), SWAT aquifer hydraulic conductivity (m/day), MODFLOW specific yield (-), MODFLOW specific storage (m-1), and MODFLOW

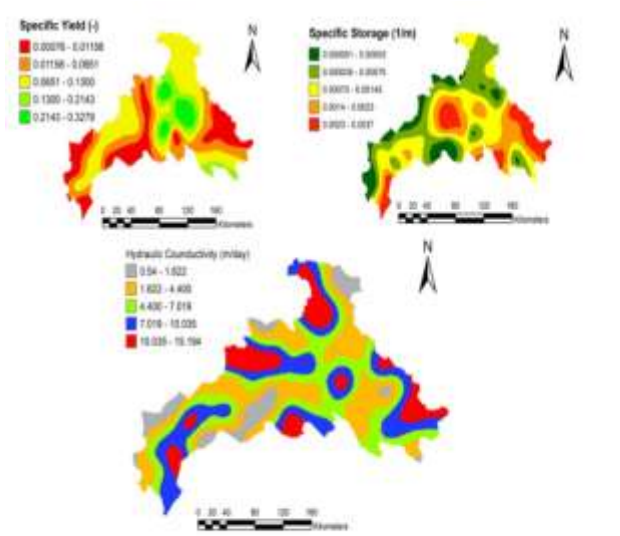

Figure 4. *Distribution of automated aquifer parameters in the Lower Zab River Basin.*

3.2. Performance of the model during validation and calibration

Table 4 shows that the integrated model outperformed the SWAT model in terms of streamflow performance statistics. The accuracy with which the QSWATMOD model captured the observed streamflow under low base flow and peak flow conditions is shown in Figure 5. In the calibration and validation stages, both models met the evaluation criteria and accurately represented streamflow [51].

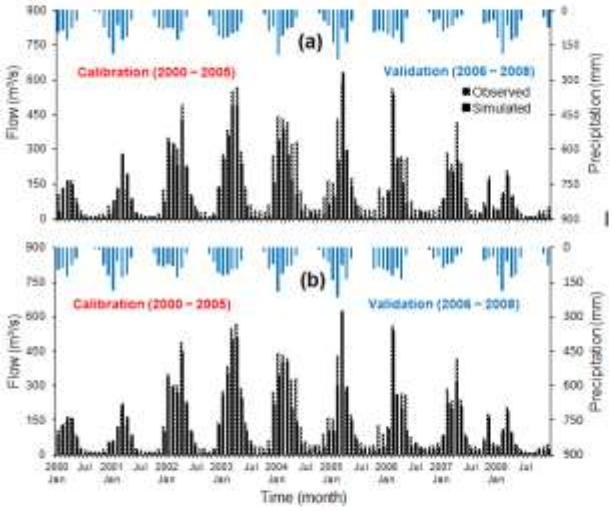

Figure 5. *Observed and simulated flow by (a) SWAT model; and (b) SWAT-MODFLOW, and precipitation at the stream station in the years 2000–2008*

Table 4. *SWAT and SWAT-MODFLOW performance metrics during calibration and verification.*

Name of the model	Calibration		Validation	
	R^{2*}	NSE**	R^{2*}	NSE**
SWAT	0.83	0.79	0.80	0.72
SWAT-MODFLOW	0.89	0.77	0.90	0.74

** Regression coefficient; ** Nash-Sutcliffe efficiency*

3.3. Groundwater recharge

Figure 6 shows the groundwater recharge distribution on average from 2001 to 2020. Significant changes in groundwater recharge over time and space are shown in the figure for the entire watershed. These patterns are evident in the monthly average recharge distribution, which falls between 0.215 and 25.052 mm/month (Figure 6.a). The complexity of groundwater recharge distribution in this study makes it challenging to correlate with the region's physical topography, although the southwest exhibits the highest recharge levels. Groundwater recharge in the study area showed a pattern of heavy precipitation during the wet season, which ran from January to March (Figure 6.c). The average recharge during the rainy season varies from 0.303 to 54.23 mm/month. In contrast, the dry season (June to September) experiences the lowest recharge values of the year, with the maximum reaching only 11.161 mm/month (Figure 6.b). Recharge rates are lower in higher-elevation areas. The recharge accounts for 15–40% of the average yearly precipitation in the Lower Zab River watershed, which includes our study area [52]. Furthermore, wintertime is when the recharge is highest and most noticeable, with February showing the highest recharge value. According to this study, the average annual precipitation in the area is caused by groundwater recharge to the tune of 0.16%.

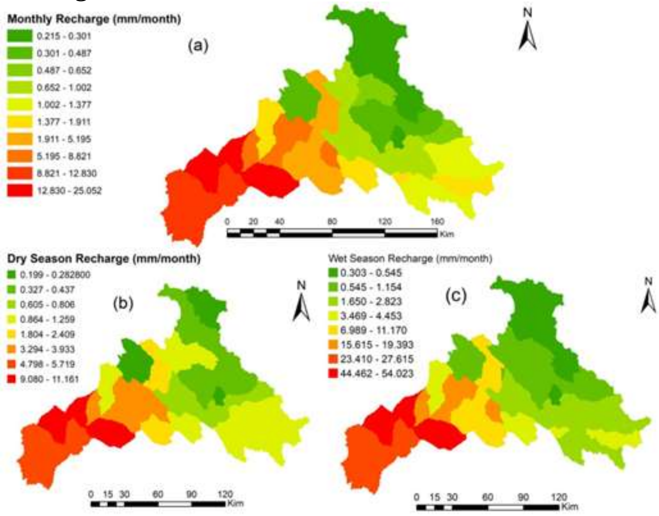

Figure 6 *(a) Monthly recharge; and (b) dry season recharge; and (c) wet season recharge in the Lower Zab River Basin.*

4. Conclusions

To assess the groundwater recharge of the Zab River basin, a numerical model approach was employed. QSWATMOD was used to determine the spatiotemporal distribution of groundwater recharge in the study region. For the linked model, observations of groundwater level and streamflow were calibrated. Streamflow measurements were conducted between 2001 and 2005. and validated from 2006–2008. The model's performance has been evaluated using the statistical parameter functions R2 and NSE. The integrated model performed more effectively throughout the calibration and validation phases when modeling the streamflow. In addition to aquifer parameter calibration, recalibrating specific SWAT parameters was a demonstrated factor in improved streamflow simulation for integrated models. The QSWATMOD model displayed spatiotemporal distribution changes over the year and determined the region's average monthly groundwater recharge.

There was a noticeable difference between the dry and wet seasons, and the model correctly represented the seasonal recharge in the area. Even though there are many urban areas in the area, 16% of the yearly average precipitation comes from groundwater recharge. Significant contributions were made by surface and lateral direct flow components, which are connected to the study area's geological characteristics. All things considered, the present study proved the usefulness and application of the QSWATMOD model for groundwater recharge analysis. Swat-Modflow displays the study watershed's groundwater recharge's temporal and spatial distribution. As such, it provides a more accurate depiction of the region's groundwater and surface water.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.

- **Author contributions:** The authors declare that they have equal right on this paper.

- **Funding information:** The authors declare that there is no funding to be acknowledged.

- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

References

[1] Arshad, A., Mirchi, A., Samimi, M., Ahmad, B., (2022). Combining Downscaled-GRACE Data with SWAT to Improve the Estimation of Groundwater Storage and Depletion Variations in the Irrigated Indus Basin (IIB). *Sci. Total Environ.,* 838, 156044.

[2] Aslam, R.A., Shrestha, S., Usman, M.N., Khan, S.N., Ali, S., Sharif, M.S., Sarwar, M.W., Saddique, N., Sarwar, A., Ali, M.U., et al., (2022). Integrated SWAT-MODFLOW Modeling-Based Groundwater Adaptation Policy Guidelines for Lahore, Pakistan under Projected Climate Change, and Human Development Scenarios. *Atmosphere,* 13,

[3] Locatelli, L., Mark, O., Mikkelsen, P.S., Arnbjerg-Nielsen, K., Deletic, A., Roldin, M., Binning, P.J. (2017), Hydrologic Impact of Urbanization with Extensive Stormwater Infiltration. *J. Hydrol.* 544, 524–537.

[4] Barron, O.V., Donn, M.J., Barr, A.D., (2013). Urbanisation and Shallow Groundwater: Predicting Changes in Catchment Hydrological Responses. *Water Resour. Manag.,* 27, 95–115.

[5] Fleckenstein, J.H., Krause, S., Hannah, D.M., Boano, F., (2010). Groundwater-SurfaceWater Interactions: New Methods and Models to Improve Understanding of Processes and Dynamics. *Adv. Water Resour.,* 33, 1291–1295.

[6] Sophocleous, M., (2002). Interactions between Groundwater and Surface Water: The State of Science. *Hydrogeol. J.,* 10, 52–67.

[7] Sharp, J.M., (2010). The Impacts of Urbanization on Groundwater Systems and Recharge. *Aquamundi,* 1, 51–56.

[8] Wang, Y., Zheng, C., Ma, R., (2018). Review: Safe and Sustainable Groundwater Supply in China. *Hydrogeol. J.,* 26, 1301–1324.

[9] Yifru, B.A., Chung, I.M., Kim, M.G., Chang, S.W., (2021). Assessing the Effect of Land/Use Land Cover and Climate Change on Water Yield and Groundwater Recharge in East African Rift Valley Using Integrated Model. *J. Hydrol. Reg. Stud*., 37, 100926.

[10] Lee, C.H., Yeh, H.F., Chen, J.F., (2008). Estimation of Groundwater Recharge Using the Soil Moisture Budget Method and the Base-Flow Model. Environ. *Geol.,* 54, 1787–1797.

[11] Scanlon, B.R., Healy, R.W., Cook, P.G., (2002). Choosing Appropriate Techniques for Quantifying Groundwater Recharge. *Hydrogeol. J*., 10, 18−39.

[12] Healy, R., Cook, P.G., (2002). Using Groundwater Levels to Estimate Recharge. *Springer,* 10, 91–109.

[13] Chand, R., Chandra, S., Rao, V.A., Singh, V.S., Jain, S.C., (2004). Estimation of Natural Recharge and Its Dependency on Sub-Surface Geoelectric Parameters. *J. Hydrol.,* 299, 67–83.

[14] Rangarajan, R., Muralidharan, D., Deshmukh, S.D., Hodlur, G.K., Gangadhara Rao, T., (2005). Redemarcation of Recharge Area of Stressed Confined Aquifers of Neyveli Groundwater Basin, India, through Tritium Tracer Studies. *Environ. Geol*., 48, 37–48.

[15] Shahul Hameed, A., Resmi, T.R., Suraj, S., Warrier, C.U., Sudheesh, M., Deshpande, R.D., (2015). Isotopic Characterization and Mass Balance Reveals Groundwater Recharge Pattern in Chaliyar River Basin, Kerala, India. *J. Hydrol. Reg. Stud*., 4, 48–58.

[16] Aslam, R.A., Shrestha, S., Usman, M.N., Khan, S.N., Ali, S., Sharif, M.S., Sarwar, M.W., Saddique, N., Sarwar, A., Ali, M.U., et al., (2022). Integrated SWAT-MODFLOW Modeling-Based Groundwater Adaptation Policy Guidelines for Lahore, Pakistan under Projected Climate Change, and Human Development Scenarios. *Atmosphere,* 13, 2001.

[17] Cheema, M.J.M., Immerzeel, W.W., Bastiaanssen, W.G.M., (2014). Spatial Quantification of Groundwater Abstraction in the Irrigated Indus Basin. *Groundwater,* 52, 25–36.

[18] Taie Semiromi, M., Koch, M., (2019). Analysis of Spatio-Temporal Variability of Surface–Groundwater Interactions in the Gharehsoo River Basin, Iran, Using a Coupled SWAT-MODFLOW Model. Environ. *Earth Sci.*, 78, 201.

[19] Dowlatabadi, S., Ali Zomorodian, S.M., (2015). Conjunctive Simulation of Surface Water and Groundwater Using SWAT and MODFLOW in FiroozabadWatershed. *KSCE J. Civ. Eng.*, 20, 485–496.

[20] Sophocleous, M.A., Koelliker, J.K., Govindaraju, R.S., Birdie, T., Ramireddygari, S.R., Perkins, S.P., (1999) Integrated Numerical Modeling for Basin-Wide Water Management: The Case of the Rattlesnake Creek Basin in South-Central Kansas. *J. Hydrol*., 214, 179–196.

[21] Gao, F., Feng, G., Han, M., Dash, P., Jenkins, J., Liu, C., (2019) Assessment of Surface Water Resources in the Big Sunflower River Watershed Using Coupled SWAT–MODFLOW Model. *Water*, 11, 528.

[22] Bailey, R.T., Wible, T.C., Arabi, M., Records, R.M., Ditty, J., (2016). Assessing Regional-Scale Spatio-Temporal Patterns of Groundwater–Surface Water Interactions Using a Coupled SWAT-MODFLOW Model. *Hydrol. Process.*, 30, 4420−4433.

[23] Techniques, M., (2005). MODFLOW-NWT, a Newton Formulation for MODFLOW-2005. *US Geol. Surv. Tech. Methods*, 6, 44.

[24] Wang, Y., Chen, N., (2021). Recent Progress in Coupled Surface–Ground Water Models and Their Potential in Watershed Hydro-Biogeochemical Studies: A Review. *Watershed Ecol. Environ*., 3, 17−29.

[25] Yifru, B.A., Chung, I.M., Kim, M.G., Chang, S.W., (2020). Assessment of Groundwater Recharge in Agro-Urban Watersheds Using Integrated SWAT-MODFLOW Model. *Sustainability*, 12, 6593.

[26] Ntona, M.M., Busico, G., Mastrocicco, M., Kazakis, N., (2022). Modeling Groundwater and SurfaceWater Interaction: An Overview of Current Status and Future Challenges. *Sci. Total Environ*., 846, 157355.

[27] Mosase, E., Ahiablame, L., Park, S., Bailey, R., (2019). Modeling Potential Groundwater Recharge in the Limpopo River Basin with SWAT-MODFLOW. Ground. *Sustain. Dev*., 9, 100260.

[28] Sophocleous, M., Perkins, S.P., (2000). Methodology and Application of Combined Watershed and Ground-Water Models in Kansas. *J. Hydrol*., 236, 185–201.

[29] Chunn, D., Faramarzi, M., Smerdon, B., Alessi, D., (2019). Application of an Integrated SWAT–MODFLOW Model to Evaluate Potential Impacts of Climate Change and Water Withdrawals on Groundwater–Surface Water Interactions in West-Central Alberta. *Water*, 11, 110.

[30] Pisinaras, V., (2016). Assessment of Future Climate Change Impacts in a Mediterranean Aquifer. *Glob. NEST J.*, 18, 119–130.

[31] Liu, W., Park, S., Bailey, R.T., Molina-Navarro, E., Andersen, H.E., Thodsen, H., Nielsen, A., Jeppesen, E., Jensen, J.S., Jensen, J.B., et al., (2020). Quantifying the Streamflow Response to Groundwater Abstractions for Irrigation or Drinking Water at Catchment Scale Using SWAT and SWAT–MODFLOW. *Environ. Sci. Eur*., 32, 113.

[32] Zambrano-Bigiarini, M., Rojas, R., (2013). A Model-Independent Particle Swarm Optimisation Software for Model Calibration. Environ. *Model. Softw.*, 43, 5−25.

[33] Yuan, L., Sinshaw, T., Forshay, K.J., (2020). Review of Watershed-Scale Water Quality and Nonpoint Source Pollution Models. *Geosciences*, 10, 25.

[34] Guevara-Ochoa, C., Medina-Sierra, A., Vives, L., (2020). Spatio-Temporal Effect of Climate Change on Water Balance and Interactions between Groundwater and Surface Water in Plains. *Sci. Total Environ.*, 722, 137886.

[35] Healy, R., Cook, P.G., (2002). Using Groundwater Levels to Estimate Recharge. *Springer*, 10, 91–109.

[36] Hung Vu, V., Merkel, B.J., (2019). Estimating Groundwater Recharge for Hanoi, Vietnam. *Sci. Total Environ.*, 651, 1047–1057.

[37] Sim¸sek, C., Demirkesen, A.C., Baba, A., Kumanlıo˘ glu, A., Durukan, S., Aksoy, N., Demirkıran, Z., Hasözbek, A., Murathan, A., Tayfur, G., (2020). Estimation Groundwater Total Recharge and Discharge Using GIS-Integrated Water Level Fluctuation Method: A Case Study from the Ala¸sehir Alluvial AquiferWestern Anatolia, Turkey. *Arab. J. Geosci.*, 13, 143.

[38] Delottier, H., Pryet, A., Lemieux, J.M., Dupuy, A., (2018). Estimating Groundwater Recharge Uncertainty from Joint Application of an Aquifer Test and the Water-Table Fluctuation Method. *Hydrogeol. J.*, 26, 2495−2505.

[39] Park, S., (2018). Enhancement of Coupled Surface/Subsurface Flow Models in Watersheds: Analysis, Model Development, Optimization, and User Accessibility by Using SWAT-MODFLOW Simulation. Available online:https://mountainscholar.org/bitstream/ handle/10217/193164/Park_colostate_0053A_15199.pdf?sequence=1 (accessed on 11 September 2024).

[40] Chung, I.M., Kim, Y.J., Kim, N.W., (2021). Estimating the Temporal Distribution of Groundwater Recharge by Using the Transient Water Table Fluctuation Method and Watershed Hydrologic Model. *Appl. Eng. Agric*., 37, 95−104.

[41] Jie, Z., van Heyden, J., Bendel, D., Barthel, R., (2011). Combination of Soil-Water Balance Models and Water-Table Fluctuation Methods for Evaluation and Improvement of Groundwater Recharge Calculations. *Hydrogeol. J.*, 19, 1487−1502.

[42] Mohammed, R., and Scholz, M., (2019). Climate change and water resources in arid regions: uncertainty of the baseline period. *Theor. Appl. Climatol.*, 137(1), 1365−1376. https://doi.org/10.1007/s00704-018-2671-6

[43] Mohammed, R., Scholz, M., (2017). Impact of Evapotranspiration Formulations at Various Elevations on the Reconnaissance Drought Index. *Water Resour. Manage.,* 31, 531-548.

[44] Park, E., (2012). Delineation of Recharge Rate from a HybridWater Table Fluctuation Method. *Water Resour*. Res., 48.

[45] Faramarzi, M., Srinivasan, R., Iravani, M., Bladon, K.D., Abbaspour, K.C., Zehnder, A.J.B., Goss, G.G., (2015). Setting up a Hydrological Model of Alberta: Data Discrimination Analyses Before Calibration. Environ. *Model. Softw*., 74, 48–65.

[46] Abbaspour, K.C., (2010). SWAT-CUP SWAT Calibration and Uncertainty Programs. Arch. Orthop. Trauma Surg., 130, 965–970.

[47] Blöschl, G., Sivapalan, M., (1995). Scale Issues in Hydrological Modelling: A Review. Hydrol. Process., 9, 251–290.

[48] Jafari, T., Kiem, A.S., Javadi, S., Nakamura, T., Nishida, K., (2021). Fully Integrated Numerical Simulation of Surface Water-Groundwater Interactions Using SWAT-MODFLOW with an Improved Calibration Tool. *J. Hydrol. Reg. Stud*., 35, 100822.

[49] Abbaspour, K.C., Rouholahnejad, E. Vaghefi, S., Srinivasan, R., Yang, H., Kløve, B.A., (2015) Continental-Scale Hydrology and Water Quality Model for Europe: Calibration and Uncertainty of a High-Resolution Large-Scale SWAT Model. *J. Hydrol.,* 524, 733–752.

[50] Ali, I. M., Naje, Ahmed Samir, Nasr, M. S., (2020). Eco-friendly chopped tire rubber as reinforcements in fly ash based geopolymer concrete. Global Nest Journal, 22(3), 342 – 347.

[51] Mohammed, Ibrahim, Hashim Al-Khalaf, Safaa K., Alwan, Husam H., Naje, Ahmed Samir, (2022). Environmental assessment of Karbala water treatment plant using water quality index (WQI). *Materials Today: Proceedings*, 60,1554 – 1560.

[52] Hassan, Ali A., Hadi, Raid T., Rashid, Adil H., Naje, Ahmed Samir, 2020. Chemical modification of castor oil as adsorbent material for oil content removal from oilfield produced water. *Pollution Research*, 39 (4),892 – 900.