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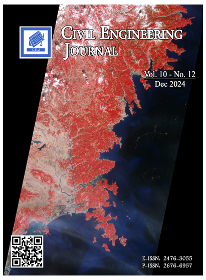

Rainfall-Runoff Modeling in a Regional Watershed Using the MIKE 11-NAM Model

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Abstract

This study used the MIKE 11 NAM model to model stormwater runoff in a northern Iraqi regional watershed of the Greater Zab River. During model calibration (2003-2017), observed data on streamflow, evaporation, and rainfall were used to optimize the nine model parameters. In order to validate the model, independent data covering the years 2018 through 2022 was used. The model's efficacy was evaluated using statistical performance metrics, including the coefficient of determination (R2), Nash Sutcliffe efficiency coefficient (NSE), and Root Mean Square Error (RMSE). During calibration (NSE = 0.81, RMSE = 2.2, and R^2 = 0.82) and validation (NSE = 0.90, RMSE = 6.9, and R^2 = 0.93), the model's performance demonstrated good agreement between simulated runoff and observed. The good agreement was for the low stream flow values compared to the high ones, due to the low number of parameters, which makes it easier to calibrate. Often, hydrological models do not capture peak flow phenomena, but there is a tendency for a good estimate of the low and medium stream flow values. Approximately 69% of the nutrient flow into the basin originated from the catchment area, which lies inside Iraq, while the remaining 31% came from the Turkey watershed. Future hydrological modeling in the area at the watershed level can utilize this model.

Keywords: MIKE11-NAM; Greater Zab River; Rainfall; Runoff.

1. Introduction

An essential aspect of creating a sustainable water management plan is a comprehensive analysis of the hydrological characteristics of the watershed. The use of hydrological models is a viable first step to enhance the reliability of streamflow forecasting. Despite significant progress in hydrological models, the main obstacle to their use lies in the basic data requirements of each model [1]. Therefore, choosing an appropriate hydrological model for a particular watershed is challenging [2]. Rainfall is the primary input to any runoff model, and converting rainfall into runoff over a drainage basin is a complex, nonlinear, time-varying, and spatially distributed process [3]. MIKE 11-NAM is an integrated conceptual rainfall-runoff model that can simulate surface, subsurface, and base flows. Both new and experienced hydrodynamic modelers can use it. In data-scarce river basins, like the Greater Zab River watershed. The Danish Hydraulic Institute is responsible for developing this model [4].

The MIKE 11-NAM model has been utilized successfully. This is particularly accurate in cases where it is not possible to use physically based distributed models because of the restricted availability of discharge data. Long-term discharge data is often lacking in water resource planning and management initiatives at project locations. Therefore, the prediction of rainfall-runoff models relies on the use of available rainfall and evaporation data to

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predict runoff [5]. The faith in the MIKE11-NAM model's capacity to provide strong scientific findings is fueled by its user-friendly interface, rich documentation and support, and widespread use. Results from a number of research studies simulating runoff processes in catchment regions all around the globe using the MIKE11-NAM model have been generally positive. Several studies, including those by [6-10], have consistently demonstrated strong model performance, especially in regions with limited accessible data. In their study, Lafdani et al. [11] used three models, including the MIKE 11-NAM model, to simulate rainfall and runoff processes. The researchers achieved positive results from their analysis. Likewise, a rainfall-runoff model was developed using the automatically calibrated MIKE 11-NAM model. The model used automated calibration to optimize parameters and achieved positive results for performance evaluation [6].

Makungo et al. [12] used the MIKE 11-NAM model to analyze an unmonitored watershed in the Quaternary sub-basin of the Nzhelele River. The acquired parameters were applied to an unmeasured watershed, yielding the best results for stormwater runoff modeling [6]. Aherwar & Aherwar [13] compared two models, namely SCS-CN and MIKE 11-NAM, to simulate stormwater runoff in the Shipra River basin in Madhya Pradesh, India. They found that the MIKE 11-NAM model outperforms the SCS-CN model in terms of performance, as evaluated using four evaluation methods. In a study, Nguyen et al. [14] evaluated the impacts of climate change-induced water flow reduction for the Nam Ou Basin, a major sub-basin in Laos of the Mekong River Basin, using the latest CMIP6 climate scenarios. The MIKE 11-NAM model and observed hydrometeorological data, and the Moderate Resolution Imaging Spectrometer (MODIS) evaporation were used. The climate change scenarios showed increases in seasonal and annual river discharges by different magnitudes in the future. Their performance was satisfactory.

Dhruw et al. [15] used the MIKE 11 NAM model to simulate the rainfall-runoff dynamics within the Ravishankar Sagar reservoir basin in Chhattisgarh. To ensure the accuracy of the estimation, they used the flow data from 2004 to 2015 for calibration and from 2016 to 2020 for validation. The MIKE 11 NAM model accurately predicted the daily runoff and reproduced the hydrological response of the Ravishankar Sagar catchment to rainfall satisfactorily. Kumar et al. [16] conducted a quantitative analysis of the hydropower potential of the Upper Beas Basin using MIKE11NAM software to estimate the available discharge. The model was calibrated and validated during June 2015 to May 2018 and June 2018 to May 2020, respectively, using daily observed discharge data at the Pandoh Dam site. The model showed good performance with a coefficient of determination (R2) of 0.82 during calibration and 0.70 during validation and a water balance of 0.01% and 18%, respectively. However, Lmax, CK1, CK2, and CQOF were found to be the most sensitive parameters during calibration. In this study, precipitation runoff was simulated using the MIKE 11-NAM model in the regional watershed of the Greater Zab River in northern Iraq. Since no effort has been made in the past to analyze the stream flow for this watershed using the MIKE 11-NAM model, the calibrated parameters of the model can be used to evaluate the impacts of upcoming hydrological events, establish design criteria, and manage water resources in the regional watersheds of Iraq and Turkey. Also, the aim of this study is to know the contribution percentage of the river basin, which lies in Turkey, to the stream flow.

1.1. Study area

The Greater Zab River is one of the major tributaries of the Tigris River. The Great Zab River Basin is located in Iraq and Turkey. Geographically, it lies within the latitude (36.25°N to 38.5°N) and the longitudinal (43.25°E to 45.1°E), as shown in Figure 1. The basin has a large area and is estimated at over 20,000 square kilometers. The Great Zab River Basin is characterized by the collection of many tributaries contributing to the region's water drainage. The main channel responsible for this drainage is the Great Zab River. The exact numbers for the highest and lowest water flow rates in the basin may fluctuate due to seasonal changes, rainfall patterns, and human influences, such as water withdrawals and land use changes. During times of wet seasons, the Great Zab River may transport large amounts of water, although its smaller tributaries may have diminished flows during dry seasons. The annual rainfall depth ranges from 300 mm to 1100 mm. The highest water flow rates in the Greater Zab River are seen in May. The annual flow rates during the period 2000–2022 had a maximum value of 1085 cubic meters per second, a minimum value of 35 cubic meters per second, and an average value of 302 cubic meters per second. The Eski Kalak station measures the average yearly water volume of 13.2 billion cubic meters that the Greater Zab River supplies to the Tigris River [17].

Monthly river flow rate data were collected from the Ministry of Water Resources in Iraq for the Eski Kalak station, covering the period 2003–2022. Meteorological data from nine stations of the watershed (Table 1) was also collected using the Infrared Precipitation Climatic Hazards Program with the station (CHIRPS) and National Aeronautics and Space Administration (NASA) data for the same period.

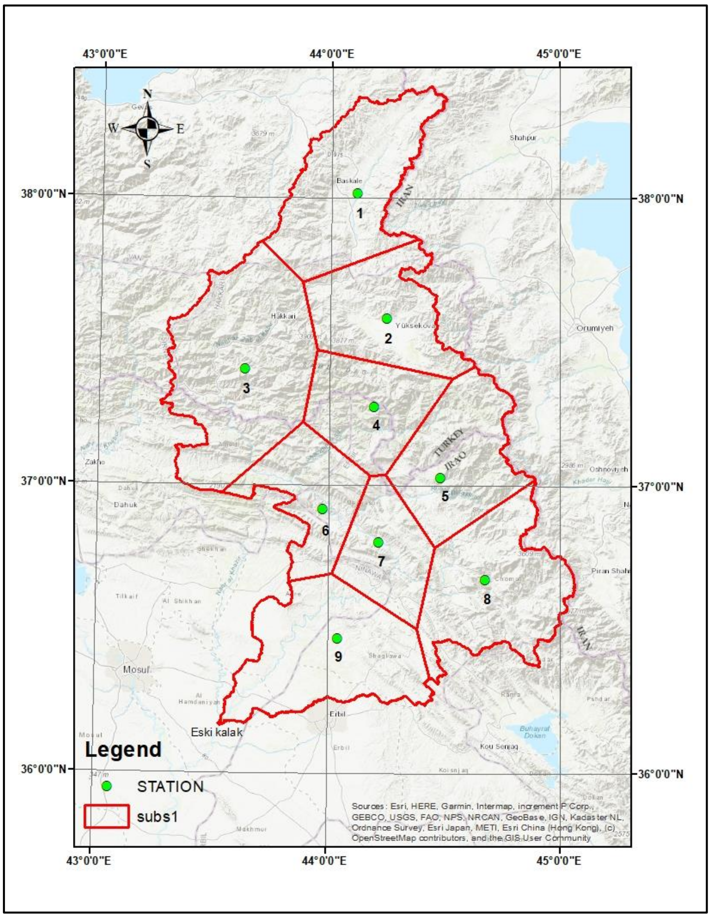

Figure 1. Study area of greater Zab river basin and the location of meteorological stations inside it

Table 1. Geographic locations of the chosen meteorological stations

No.	Name of Station	Longitude (degree)	latitude (degree)	Location
1	Station 1	44.11277928	38.0165351	Turkey
2	Station 2	44.24405129	37.58019224	Turkey
3	Station 3	44.19382706	37.2725822	Turkey
4	Station 4	43.62901807	37.40342294	Turkey
5	Station 5	44.47953732	37.02741469	Iraq
6	Station 6	43.97174222	36.91760416	Iraq
7	Station 7	44.21518431	36.80300276	Iraq
8	Station 8	44.67479236	36.67533515	Iraq
9	Station 9	44.04086389	36.4667636	Iraq

1.2. Input Data

The calibration of the MIKE11NAM model, the determination of watershed characteristics, and the definition of beginning conditions need the acquisition of meteorological data for the Greater Zab Basin and the observed discharge data for the Eski Kalak station. Time series data of evapotranspiration and precipitation have significant importance in meteorological data. Using this information, the model produces data on subsurface flow contributions to the channel and a sequence of catchment runoff over time, in addition to other elements of the hydrological cycle's land phase, like groundwater levels and soil moisture content.

1.3. Rainfall

Daily precipitation data for nine stations were collected using the Infrared Precipitation Climatological Hazards software with the station CHIRPS for the period from 2003-2022. The average of rainfall in (mm) of the nine stations is shown in Figure 2. To validate and calibrate the model, these data were required. Data for the hydrological years (2003-2017) were used to calibrate the model, and data for the hydrological years (2018-2022) were used to validate the model.

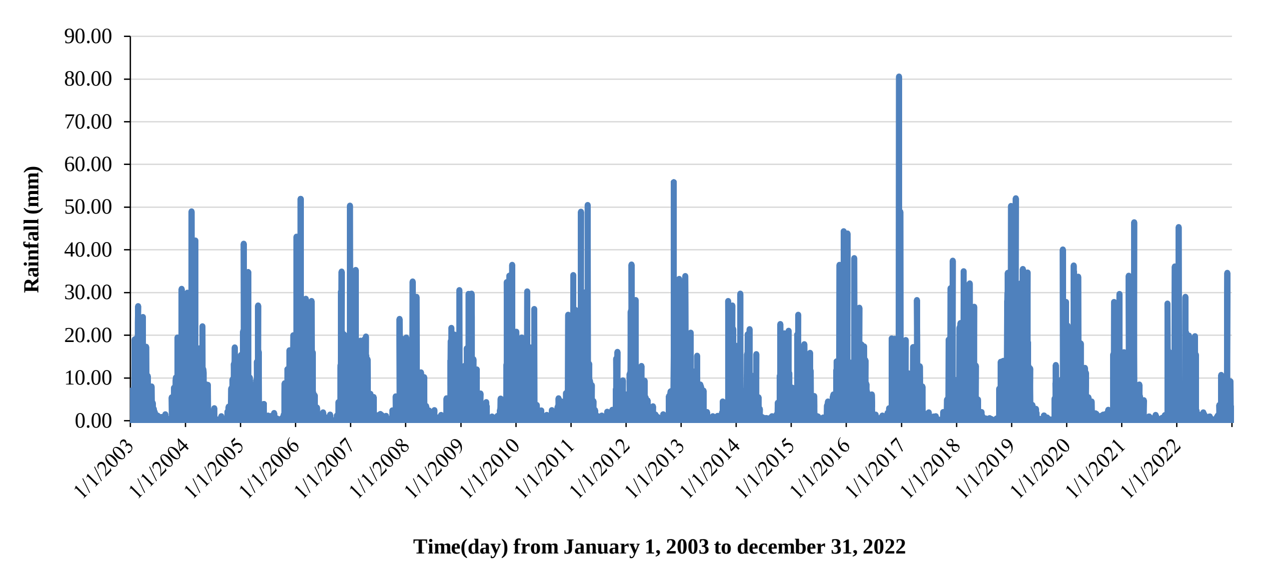

Figure 2. Average rainfall of the 9 stations for the period from 2003-2022

1.4. Potential Evapotranspiration

The daily potential evapotranspiration data in this study (mm/day) were used from 2003-2017 for calibration purposes and from 2018-2022 for validating the model. Potential evapotranspiration was estimated based on a total accumulation of many steps. Daily maximum and minimum temperatures and radiation values were used for this process. These data for nine stations were generated from the National Aeronautics and Space Administration (NASA); evapotranspiration was calculated using Equation 1:

$$PET = mR\left(T_{avg} + 17.8\right)(T_{max} - T_{min})^{0.5} \tag{1}$$

where PET is Potential Evapotranspiration (mm/day), m is Constant = 0.0009384, R is Radiation (MJ/m^2), T max is Maximum Temperature (℃), T min is Minimum Temperature (℃).

1.5. The Observed Discharge

In order to validate and calibrate the model, discharge measurements that were recorded at the watershed's outflow must be compared to the simulated runoff. This study utilized monthly discharge data of the Eski Kalak station, which lies downstream of the catchment area, measured in cubic meters per second as shown in Figure 3 (Ministry of Water Resources in Iraq). The data from 2003-2017 was used for calibration, while the data from 2018-2022 was used for verification. The discharge was treated as instantaneous.

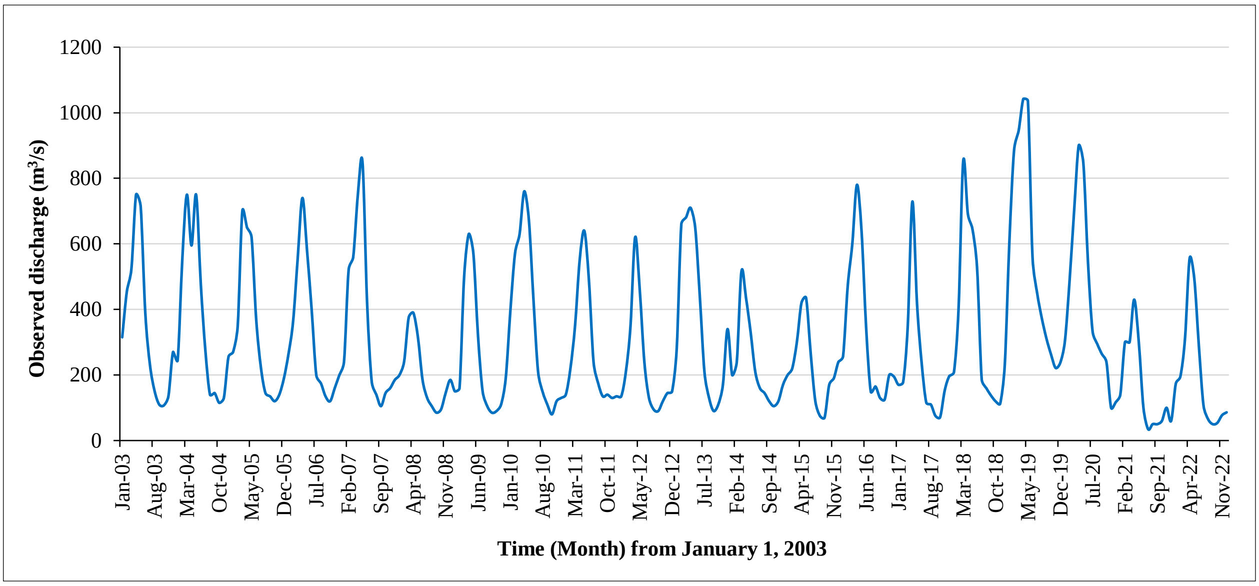

Figure 3. Observed discharge at Eski Kalak station for the period from 2003 to 2022

2. Materials and methods

2.1. (MIKE 11 _ NAM) Model

A hydrological model called MIKE 11 NAM was used to simulate the processes of rainfall and runoff in a watershed. NAM, which is a component of the MIKE 11 River modeling system's rainfall-runoff. The concept of rainfall-runoff may also be used to describe the lateral inflows from one or more contributing catchments into a river basin (Technical University of Denmark; [4]). With this method, a single catchment, a major river basin with several smaller basins, and an intricate network of rivers and channels may be analyzed using the same modeling framework. NAM stands for "Nedbør--Afstrømnings-Model," which is a Danish phrase. Which refers to the process of modeling the relationship between rainfall and runoff. Resources [4] which first created this model. The MIKE 11-NAM model allows for the simulation of the rainfall-runoff process over a wide geographical and temporal extent. The model used in the majority of calibration and validation procedures consistently underestimates the highest flow rates. Nevertheless, the estimation of low flows was accurately conducted [12]. The necessary data for the model were formatted and sent to the modeling environment.

2.2. Model Calibration and Validation

Direct field data of the model parameters cannot be measured, which are necessary for the calibration of the model. Automated calibration was used to establish the model parameters before model calibration. Subsequently, they were adjusted manually using a trial-and-error approach, as described by Yapo et al. [18]. During manual calibration, the model parameters are modified via a process of trial and error. Automatic model calibration allows for a clear assessment of the simulation performance of the model. Additionally, the calibration procedure is completed in a shorter timeframe compared to earlier techniques [19]. It is frequently not possible to accurately model every important activity in a watershed using single-objective automatic calibration. Therefore, for a rainfall-runoff model, a multi-objective calibration strategy is preferred [20]. Figure 4 shows the structure of the (MIKE 11 NAM) model. The MIKE 11 NAM model was used to simulate monthly runoff in the regional Greater Zab River catchment [3, 4]. In this study, the model parameters were changed to minimize the discrepancies between the simulated and actual flow rates. This process of model calibration was carried out on a monthly basis. Using a separate dataset, the model was verified for the years 2018–2022 and calibrated for the years 2003–2017.Nine parameters were used to calibrate the MIKE 11 NAM model: the time constant of mean flow (CKIF), the time constant of inter- and onshore flow routing (CK12), the root zone threshold value of the time constant of core flow (TOF), the maximum amount of water in the reservoir surface storage (Umax), the maximum amount of water in root zone storage (Lmax), the overland runoff coefficient (CQOF), and the time constant of base flow routing (CKBF), as shown in Table 2.

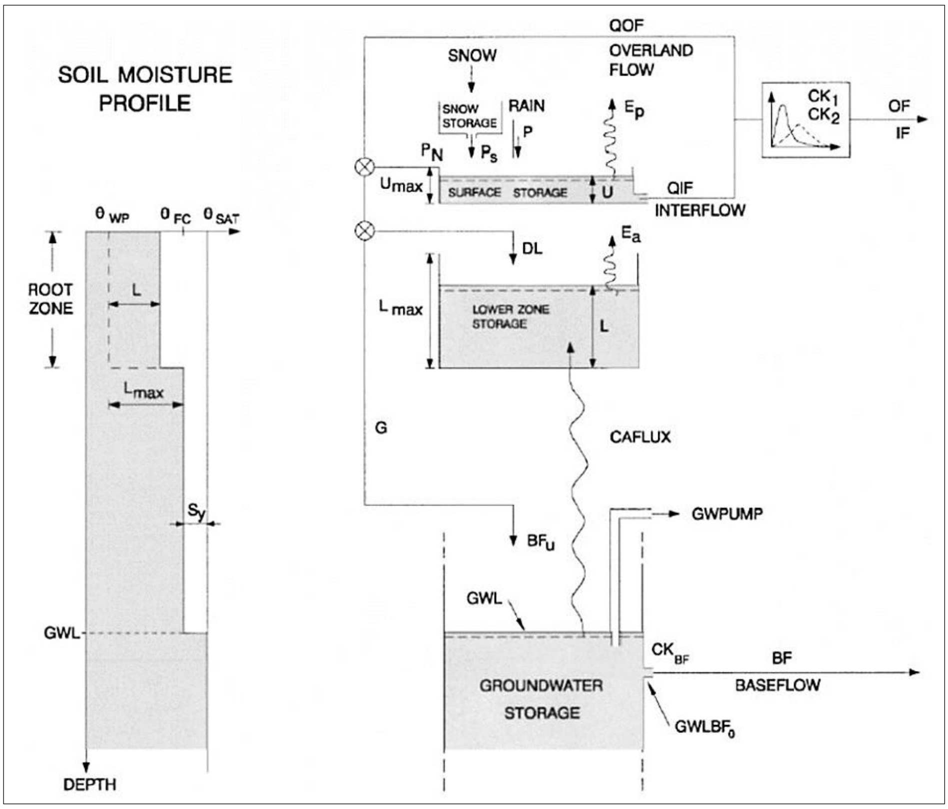

Figure 4. The MIKE 11 NAM model's structure

Table 2. Input parameters used for calibrating the model

Parameters	Description	Lower bound	Upper bound	final value	Unit
Umax	The maximum water content in the surface storage	5	35	5.6	[mm]
Lmax	The maximum water content in the lower zone storage	50	350	56	[mm]
CQOF	Overland flow runoff coefficient	0	1	0.453	[–]
CKIF	The time constant for routing interflow	500	1000	685.9	[h]
TOF	Root zone threshold value for the overland flow	0	0.99	0.629	[–]
TIF	Root zone threshold value for interflow	0	0.99	0.887	[–]
TG	Root zone threshold value for GW recharge	0	0.99	0.038	[–]
CKBF	The time constant for routing base flow	500	5000	3948	[h]
CK1,2	The time constant for overland flow	3	72	66.65	[h]

2.3. Evaluation of Model Performance

To calibrate and verify the model, it is necessary to get quantitative data that can be used to assess the model's performance. Monthly streamflow data for the Greater Zab River were used to assess the model's effectiveness. To judge the performance, the output of the water balance in the river catchment area was the discharge time series that was compared to the flow rates that had been collected. Statistical performance indicators were used as in Equations 2 to 4. When the (RMSE) equals 0 (zero), as in Equation 2, there is a perfect match between the predicted values and the observed. According to Singh et al. [21], low RMSE values signify strong model prediction when they are less than half the standard deviation of observed (measured) data. The range of the (NSE) coefficient is $-\infty$ to 1. When NSE equals 1, it signifies a perfect match between the actual and expected values (see Equation 3). Performance levels that fall between (0.0 - 1.0) are typically regarded as acceptable, whereas performance levels below 0.0 are deemed undesirable. Equation 4 gives the coefficient of determination, R^2, which is a number between 0 and 1. A higher value of R^2 means less error variance. Typically, an $R^2 > 0.5$ is considered acceptable [22].

$$RMSE = \frac{\sqrt{\sum_{i=1}^{n}(Q_i^{obs}-Q_i^{sim})^2}}{n} \tag{2}$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(Q_i^{obs}-Q_i^{sim})^2}{\sum_{i=1}^{n}(Q_i^{obs}-\bar{Q}_i^{obs})^2}\right] \tag{3}$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}(Q_i^{obs}-\bar{Q}_i^{obs})\,(Q_i^{sim}-\bar{Q}_i^{sim})\right]^2}{\sum_{i=1}^{n}(Q_i^{obs}-\bar{Q}_i^{obs})^2\,\sum_{i=1}^{n}(Q_i^{sim}-\bar{Q}_i^{sim})^2} \tag{4}$$

In this case, n stands for the duration of the series, Q_i^{sim} is simulated flow, Q_i^{obs} is observed flow, $\bar{Q}_i^{obs}$ is the average of the observed flow, and $\bar{Q}_i^{sim}$ is the average of the simulated flow.

3. Results and Discussion

Nine model parameters were used in the automated calibration approach, which provided parameter experiments based on the objective function and its routine. By adjusting the parameters within a predefined range to choose optimal values, automated calibration was used to discover the best objective functions. The optimized parameters of using the automatic calibration are shown in (Table 2). The MIKE 11-NAM model was calibrated for the period from 2003 to 2017 and then verified for five separate years from 2018 to 2022. Figure 5 shows the comparison between the observed and simulated discharge at the outflow of the catchment area over the calibration period. Likewise, Figure 6 shows the comparison between the observed and simulated discharge during the validation period. Table 3 shows that the model performed well during the calibration and validation period using statistical indicators (NSE, R2, RMSE). Thus, the results show good agreement between the simulated discharges and observed at medium and low flows and are acceptable at high discharges. The total simulated water volume of the Greater Zab River is 9.2 billion cubic meters annually. Figure 7 displays the flow rate at the boundary between Turkey and Iraq. Which represents the contribution of the sub-basins in Turkey (meteorological stations 1, 2, and 3, Figure 1) From 2003 to 2022, the basin of this river in Turkey contributes 31% of the entire predicted basin flow, with an annual volume of 2.9 billion cubic meters so Within the north of Iraq, the remaining volume of 6.3 billion cubic meters represents the contribution of the basin inside Iraq regions with the water resource for the Tigris River, about 69% of the whole simulated flow of the Greater Zab River.

Table 3. Evaluation of the models' statistical performance

Statistical criteria	Calibration period	Validation period
NSE	0.81	0.9
R^2	0.82	0.93
RMSE	2.2	6.9

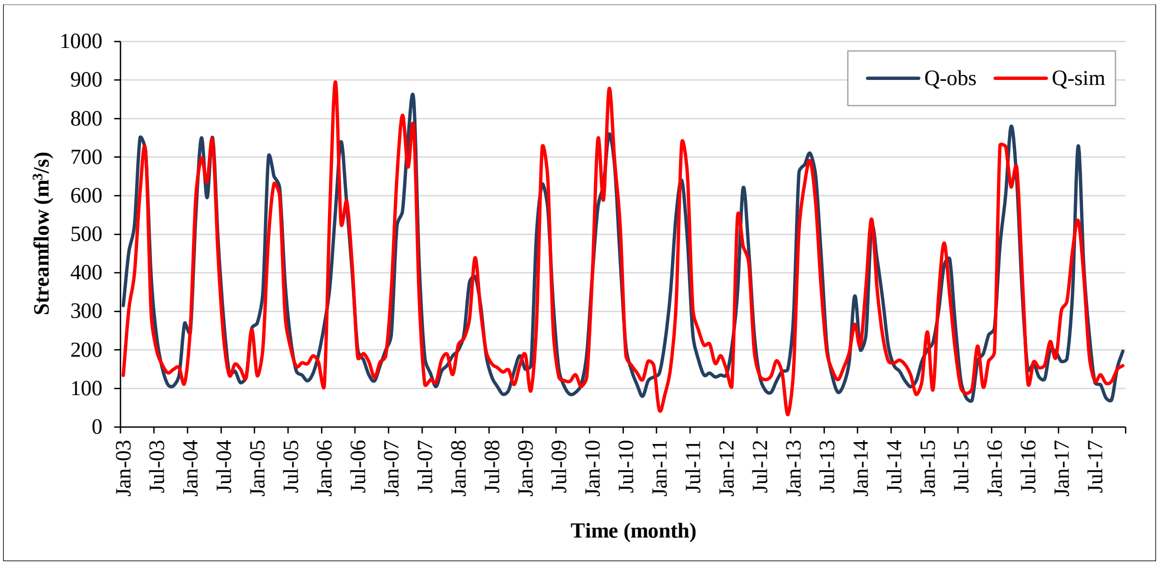

Figure 5. Simulated and observed stream flow results during the calibration process (2003-2017)

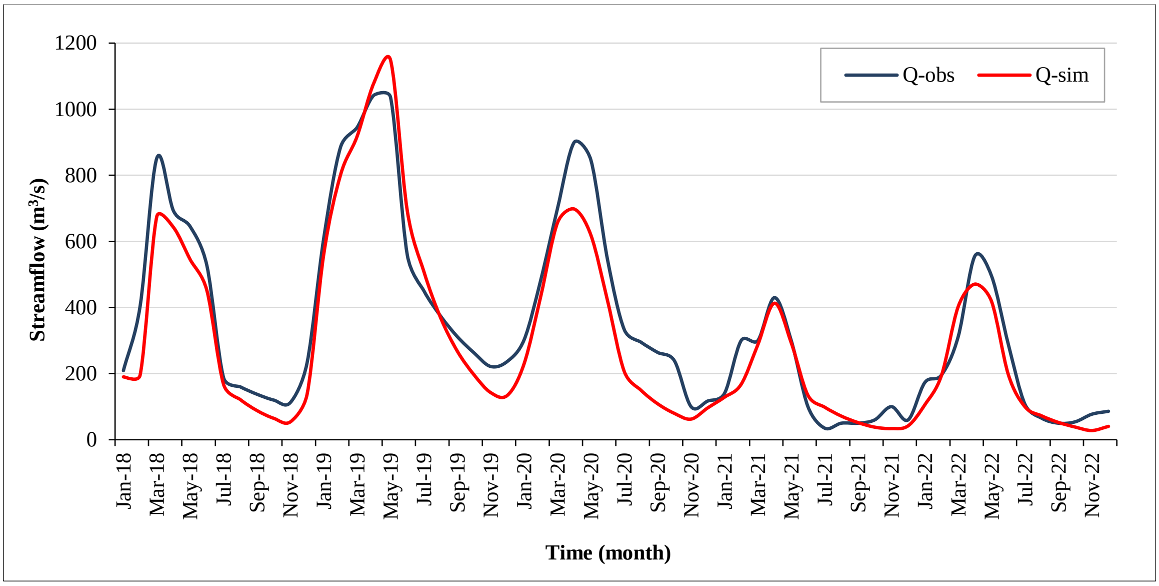

Figure 6. Simulated flow rate during the validation (2018-2022)

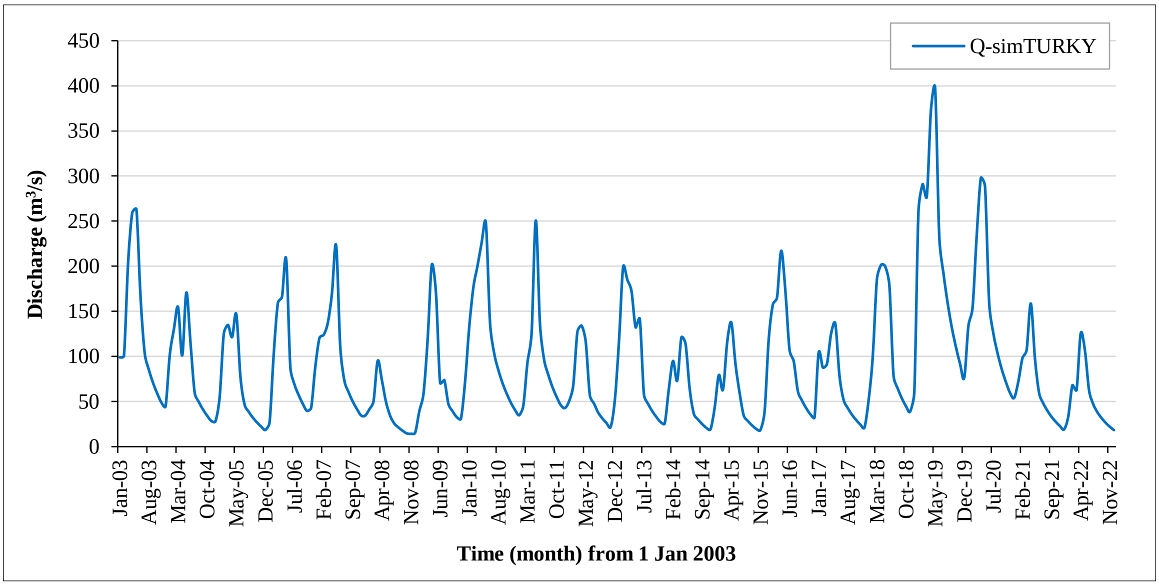

Figure 7. Simulated inflow of runoff into the Iraq is region of the greater Zab basin from the subbasins in Turkey (2003 - 2022)

4. Conclusion

By using the MIKE 11-NAM model, this study attempts to enhance and analyze the hydrological process of runoff in the Greater Zab River's regional catchment area. This research used an automated calibration approach to adjust the nine parameters of the models based on the observed streamflow of the Greater Zab River. Statistical indicators were used to evaluate the model's performance, which was determined to be satisfactory throughout both the validation and calibration stages. Therefore, the model's ability to accurately simulate runoff was established, as evidenced by its strong agreement with actual runoff. Based on this hypothesis, a simulation was performed to estimate the runoff from the subbasins in the Turkish part of the basin and its potential impact on the total flow. It turns out that if Turkey built dams along the river, the total stream flow would decrease by 31%. So, there is an expected reduction in flow rates due to climate change, which will lead to drought conditions in the future. Hence, decision-makers need to develop appropriate strategies to regulate runoff, improve its use, and improve water resource management. The study's findings are valuable for decision-makers and water policymakers for this regional watershed due to a shortage in hydrological and soil data, given that hydrological modeling in this basin can be accomplished with success using the MIKE 11 NAM model.

5. Declarations

5.1. Author Contributions

Conceptualization, A.H.S. and T.S.K.; methodology, A.H.S.; software, A.H.S.; validation, A.H.S.; formal analysis, A.H.S. and T.S.K.; investigation, A.H.S. and T.S.K.; resources, A.H.S.; data curation, A.H.S.; writing—original draft preparation, A.H.S.; writing—review and editing, A.H.S. and T.S.K.; visualization, A.H.S.; supervision, T.S.K. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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