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ORIGINAL STUDY

Hydrological Model of the Diyala River Watershed in Iraq Using Soil Water Assessment Tool

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Abstract

The motivation of the present study is to study and address the limitations imposed on hydrological models and the spatial and temporal distribution of streamflow in the Watershed Diyala River (WDR) from January 1996 to April 2023, which has an area of 25,652 km^2, which is considered an important source of water for central and southern Iraq, to enable decision-makers to make a future management plan for streamflow. To achieve this motivation, the SWAT model was used and fed by input data such as a digital elevation model with a 30 m resolution, a soil map, the land use and land cover map with a spatial resolution of 30 m, weather data, and the daily streamflow data. Using the SUFI-2 algorithm and SWAT-CUP, the model was calibrated automatically. Statistically, using the R^2, NSE, and Pbs, the performance of the model was evaluated. The statistical analysis displays a perfect match between simulated and observed values when calibrating and verifying the model for streamflow. The results indicate that the monthly evapotranspiration rate and streamflow constitute 65% and 37% of the rainfall in WDR, respectively, and that the annual average surface runoff ranged from 320.358 to 8.325 m^3/s. Therefore, it is possible to rely on the calibrated model, successfully verified with high reliability, to simulate the hydrological model in WDR.

Keywords: SWAT model, Hydrological model, Diyala river watershed, Water balance

1. Introduction

The hydrological model is a necessary and important tool for managing the environment and water resources [1]. It is used to convert rainfall to Surface Runoff (SurQ) by applying different physical equations in the catchment area [2]. Human activities cause serious transformations in aquatic ecosystems and the resources they produce by changing land use, water flow routes, and thus the components of the hydrological cycle [3]. Expanded settlement areas and agricultural works influence various hydrological processes, such as evapotranspiration (ET), infiltration, SurQ, and water productivity [4]. In hydrological model, it is important to monitor and model SurQ, temporally and spatially and direct them into stream channels to develop an integrated, applicable strategic policy to distribute it in catchment areas [5]. Watersheds are affected by a complex set of factors, such as terrain, weather, land use, and a soil characteristic, which makes estimating hydrological components require advanced techniques to obtain reliable data to conduct the study [6].

One of the best hydrology models is the Soil and Water Assessment Tool (SWAT), a Geographic Information System (GIS)-based hydrological model.

SWAT application in many studies in the world, some researchers used the SWAT model in the Ouergha watershed in Morocco from 1990 to 2013, and they were able to show the spatial and temporal distribution of the hydrological components by creating a map in the catchment

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while studying the water balance. They showed that evaporation constitutes 54% of the total rainfall and that surface runoff constitutes 29% of the total rainfall. Therefore, this study enabled decision-makers to protect water resources in the future [7].

Others; used hydrological models to help develop different hypothetical scenarios for changing land use land cover (LU/LC), and find changes that occur in various hydrological variables, when calculating components of water balance in Vea Catchment, West Africa, in 2020. The results showed that changing LU/LC to forest with agricultural lands; would reduce evaporation by 7% and average water production would increase by 9% when compared to the baseline scenario before the LU/LC change. This procedure will help in planning the management of water resources in the future [8].

There are some studies conducted on DRW, the most important of which studied the effect of a change in Lu/Lc on water resources in Iraq using the SWAT model, which showed that; conducting a hydrological model can be used SWAT model without any problem and can be applied calibration and validating of the model depending on the flow that entering to stations in DD and HD [9]; also runoff was prediction in Galal Badra in Wasit, Iraq, shows that the average surface runoff was about 25.7% of the total precipitation during the study period, and it is possible to apply hydrological models to provide successful water management in the catchment area by storing the largest amount of rainwater in peak times and utilizing it in times of drought [10].

Others used remote sensing and the HEC-RAS hydraulic model to simulate floods and their impacts on the Hemren reservoir in DRW. The study showed that it is possible to rely on the results of the model to find solutions to the problem of flooding that occurs in DRW by creating an artificial canal linking it with the Hemren reservoir towards the lowlands and connecting it to the Tigris River when needed [11].

In the present study, the WDR in Iraq was considered as a case study, which is considered one of the most important watersheds in the northern region of Iraq and represents an important source of water for central and southern Iraq. The study aims to create a hydrological model to simulate SurQ spatially and temporally and check the usability of the SWAT model for WDR for the period from January 2000 to April 2023 to enable decision-makers to make decisions to plan and manage WDR.

2. Material and methods

2.1. Study area

WDR is within the Iranian and Iraqi borders [9]; 41% of the area is located within the Iraqi border; it is between latitudes 33.95 N and 35.83 N and longitudes 44.5 E and 47.83 E; it extends to an area of, 25,652 km^2. The Diyala River (DR), formed in the WDR, is an important water source for the southern areas of Iraq [12,13]. Along DR, two dams have been built, which are Hemrin Dam (HD) and Derbindikhan Dam (DD) according to Fig. 1. WDR changed from 58 to 3351 m above the seawater level. The elevation decreases gradually from the northeast to the southwest, with the highest point reaching 3351 m, the lowest point reaching 96 m, and the mean elevation being 990 m. The climate of WDR is classified as arid and semi-arid; the annual precipitation is 32 cm and falls for six months starting in November, whereas the mean temperature is 20 °C [Iraqi Meteorological Office, Iraq, 2023, unpublished data]. The area contains three meteorological stations in Halabja, Sulaymaniyah, and Khanaqin with latitudes (longitudes) of 33.19 N (45.90 E), 34.35 N (45.39 E), and 35.53 N (45.46 E), respectively. The average wind speed is 1.91 m/s, so the study area contains two flow gauging stations located at HD and DD. The average daily discharge from 1984 to 2022 entering Hemrin gauging station was 129.7 m^3/s, with a maximum and minimum discharge of 1168 m^3/s and 1 m^3/s, respectively, while the average daily discharge that came to Derbindikhan gauging station was 120.5 m^3/s, with the maximum and minimum discharge of 1114 m^3/s and 2.1 m^3/s, respectively [Administration of Hemrin and Derbendikhan Dams, Iraq, 2022, unpublished data].

2.2. Description of SWAT model

SWAT is a physical-based model that is easy to implement, roughly distributed, has continuous time steps, is free and available to all, and can be carried out for the catchment arid or semi-arid. It was developed by the Agricultural Research Service (ARS) of the United States Department of Agriculture (USDA) [14]. SWAT needs data on the weather, soil categories, land topography, and Lu/Lc that occur in the catchment area [15]. The SWAT model is characterized by its ability to deal with the inputs of physical data for soil characteristics, Lu/Lc, weather, and topography during simulation with high computational efficiency, and simulations of large and small watersheds can be performed with less time and cost [16]. The methodology to

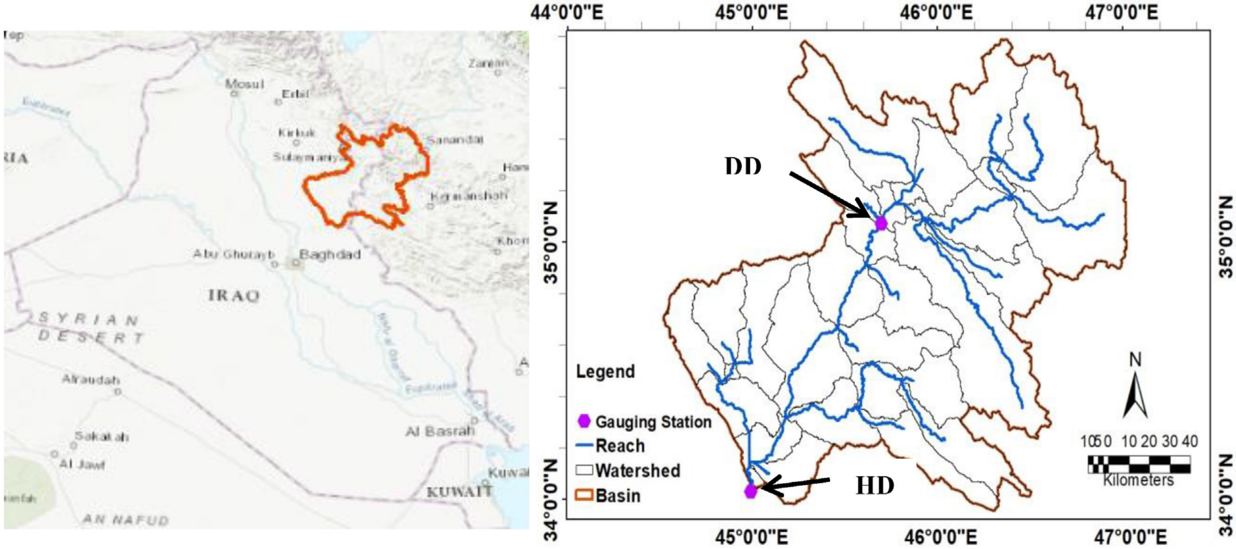

Fig. 1. Location of study area.

complete the study requirements in SWAT model was carried out according to the schematic diagram in Fig. 2.

2.3. Input data in SWAT

Digital elevation model (DEM) was used in the model with 30 m resolution, which was taken from the Shuttle Radar Topography Mission (SRTM) downloaded from the site, http://earthexplorer.usgs.gov/ on 15 October 2021, which was used for delineation of the watershed, streamflow extraction, slope, and dividing the watershed into sub-watersheds [17]. The entered data is displayed on the global coordinate system and referenced geographically to the World Geodetic System (WGS84) for zone 38 N, as shown in Fig. 3A.

Based on DEM collected the watershed was split into 33 sub-watersheds. DEM was used to extract landform parameters such as the amount of land slope and the length of the slope; and determine the flow paths depending on the threshold of each area [18]. Lu/Lc maps are very important in the hydrological modeling process because they affect the amount of SurQ that is transported from the catchment area of DR. The acquisition date for the imagery in 2020 was September 20, with a spatial resolution of 30 m, it was downloaded from, https://erthexplorer.usgs.gov. Then it prepares maps of Lu/Lc in 2020 in WDR based on the Landsat 8 images, as shown in Fig. 3B. Lu/Lc was classified into five categories: built-up area, agricultural area, water, shrub area, and barren area, with percentages of 5.21, 0.37, 2.02, 0.87, and 91.53%, respectively.

The soil used map was downloaded from, https://www.fao.org; on 25 September 2021 as shown in Fig. 3C. Soil maps of WDR were joined with soil databases of SWAT model using assigned four-letter codes for soil categories as shown in Table 1. Daily weather data such as precipitation, temperature, wind speed, relative humidity, and solar radiation were downloaded from the site, https://swat.tamu.edu/data/cfsr, according to Fig. 3D, 27 weather stations distributions used in WDR. The land slopes in the study area were classified into several groups according to Fig. 3E. The daily streamflow data was obtained at HD and DD from 1996 to April 2023 [Administration of Hemrin and Derbendikhan Dams, Iraq, 2022, unpublished data].

2.4. Models in SWAT

The watershed is split into many small sub-watersheds, and all sub-watersheds are divided into many Hydrologic Response Units (HRU).

Each HRU has the same soil, slope, and Lu/Lc. During the simulation of the SWAT model, the hydrological cycle depends on the water balance equation can be represented by equation (1), which simulates the hydrological balance in each HRU of the catchment area [19,20]:

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - ET - W_{seep} - Qgw \right) \tag{1}$$

Where,

SW_t = Final water in soil (mm).

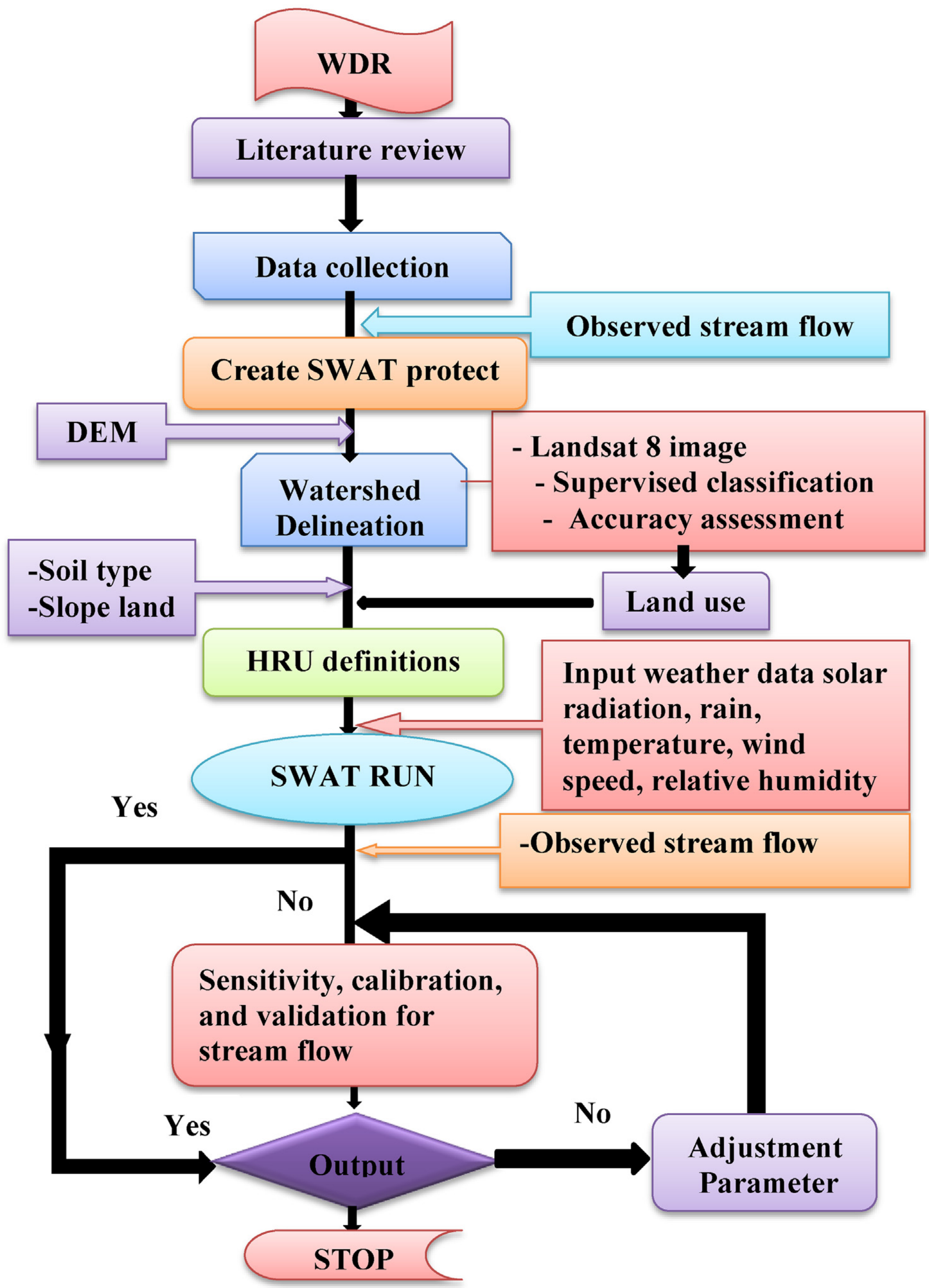

Fig. 2. Flow chart diagram of the methodology.

SW_0 =Initial water in soil on each day (mm).
t = Time in days.
R_{day} = Precipitation on day (mm).
Q_{surf} = Surface runoff on day (mm).
ET = Evapotranspiration values on day (mm).
W_{seep} = Water that comes to the unsaturated zone on day (mm).
Qgw = is the comeback flow on day (mm(.

To estimate SurQ the Curve Number (CN) method was used as shown in equation (2) [15].

$$Q_{Sur} = \left(R_{day} - 0.2\,S\right)^2 \Big/ \left(R_{day} - 0.8\,S\right)^2 \tag{2}$$

Where, Q_{sur} is the accumulated of runoff (mm), R_{day} is the depth of the rainfall (mm), S is the retention parameter which calculated from equation (3) [20]:

$$S = 254\left[\frac{100}{CN} - 1\right] \tag{3}$$

The CN values are change from zero 100.

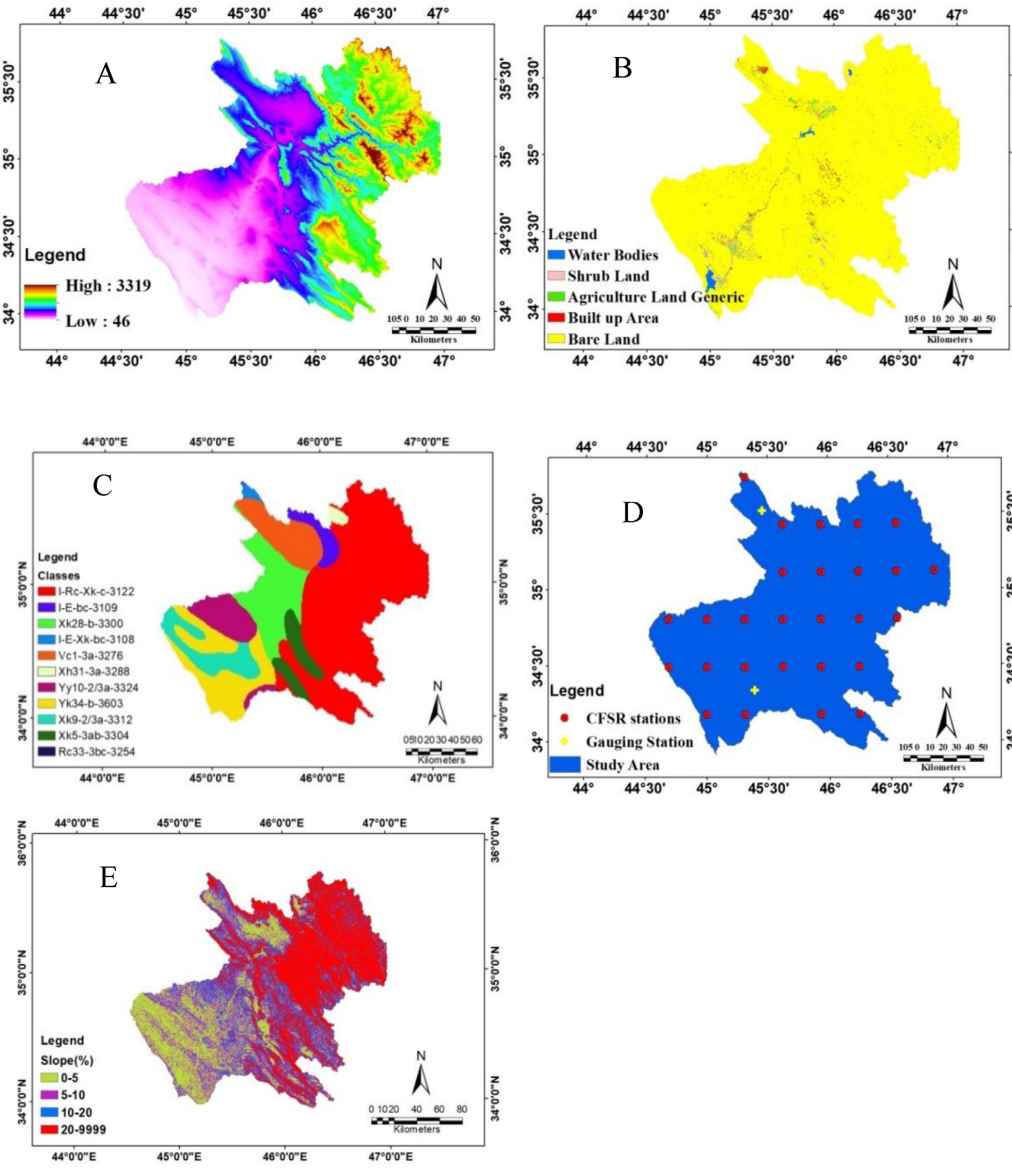

Fig. 3. Maps of input data in SWAT model; A) DEM; B) Lu/Lc in 2020; D) Soil categories; D) Weather stations; E) Slope area.

2.5. Model setup

Delineation aims to divide the watershed area into several hydrological connected sub-watersheds for easy modeling in SWAT [21], which involves first creating a project setup and then creating the input data; finally, it will obtain the topographic report for the study area. The Lu/Lc and soil categories were defined and classified, then loaded into SWAT model to construct a lookup table to link with SWAT land categories in the database. Then, the thresholds of HRU multiple with zero threshold percentages, the land use, soil class, and slope land percentage over the sub-basin area were taken without approximation [22]. The next step is the definition of weather data, which has tabs for rainfall, solar

Table 1. Classification of soil in WDR

Code soil in FAO	Code in SWAT	Areas (%)	Soil type
3108	I-E-Xk-bc-3108	0.55	Loam
3109	I-E-bc-3109	2.70	
3122	I-Rc-Xk-c-3122	47.34	
3254	Rc33-3bc-3254	0.02	
3276	Vc1-3a-3276	7.73	Clay
3288	Xh31-3a-3288	0.74	Clay Loam
3300	Xk28-b-3300	12.22	
3304	Xk5-3ab-3304	4.33	
3312	Xk9-2/3a-3312	6.36	
3324	Yy10-2/3a-3324	6.12	Clay
3603	Yk34-b-3603	11.90	Loam

radiation, wind speed, relative humidity, and temperature, which need daily input data. If the study area contains a sufficient number of meteorological stations, then they are collected and arranged in tables that are compatible with SWAT format [23]. In the event of data loss, the weather generator located in SWAT could be determined to generate weather data, which has been downloaded from https://swat.tamu.edu/data/.

To conduct the simulation process, it needs to specify the beginning and end of the simulation period, the period for the simulation (daily, monthly, or yearly), and then run SWAT with an appropriate warm-up period of no less than three years [24]. The results that will be obtained in this period are initial values for hydrological components with default parameters in the equations used in SWAT. Therefore, it is necessary to calibrate and verify the results to obtain the modified values of the parameters until there is a reasonable match between the observed and simulated values.

3. Performance of the model

The performance outputs of SWAT were evaluated statistically according to coefficient of determination (R^2) whose values range between (0–1) best results when the value is close to 1, the efficiency of Nash-Sutcliffe (NSE) whose values range from ($-\infty$ to 1); the best value of NSE when approaching to one; and percent bias (Pbs) is calculated as a percentage [25,26]. The performance of the model in SWAT depends on the values according to Table 2.

4. Principle of sensitivity, calibration and validation model

The sensitivity analysis is the entering of different values for the parameters and determining the amount of change that will occur in the model output [29]. It is necessary to conduct the sensitivity analysis to find the main parameters that are most sensitive for any watershed area to minimize the parameters number that are needed when conducting the calibration and validation of SWAT model.

Calibration is the process of getting to know and amending input parameters to the observed value, whereas validation is the process of comparing outputs SWAT with an independent dataset without parameter changes in calibration [14]. Parameter values that were used in the calibration should be within the acceptable range to minimize uncertainties in the simulation. There are several methods of calibration, including automatic calibration, trial and error, and calibration that combines both methods. In the last method, automatic calibration is performed, and then the initial values of the parameters are selected by the trial and error method (or vice versa), which is more accurate [30]. When the typical parameter values that lead to the best match between the simulated and observed values are found, the simulation ends.

5. Results and discussion

5.1. Sensitivity analysis

To save time during calibration, sensitivity analysis for streamflow was carried out before the calibration. Initially, SWAT model was run with initial parameters. Then, by using the Sequential Uncertainty Fitting (SUFI-2) algorithm in SWAT- Calibration and Uncertainty Programmes (CUP) package, automatic calibration was used.

SWAT-CUP links all calibration procedures into one interface with SWAT for easy knowledge of the parameters that need to be changed, specifies the lower and upper limits of the parameter and does

Table 2. Statistical parameter performance values that were recommended [27,28]

Performance Rating	P_{bs} (%)	R^2	NSE
Very good	$P_{bs} < \pm 10$	$0.8 \le R^2 \le 1.0$	$0.75 < NSE \le 1.00$
Good	$\le P_{bs} < \pm 1510 \pm$	$0.7 \le R^2 \le 0.75$	$0.65 < NSE \le 0.75$
Satisfactory	$\le P_{bs} < \pm 2515 \pm$	$0.5 \le R^2 \le 0.6$	$0.50 < NSE \le 0.65$
Unsatisfactory	$P_{bs} > \pm 25$	$R^2 < 0.5$	$NSE \le 0.50$

not exceed them for ease of use, and reduces time wasted during calibration by standardizing calibration steps [31].

When get a good match between simulated and observed values, parameters are copied to SWAT database instead of default parameters. For streamflow, the global sensitivity analysis was conducted for twenty parameters that were connected with SurQ according to previous studies [32]. Seven main parameters were selected for WDR, which represented the most sensitive. Table 3 shows the best parameters used in calibration and verified SWAT model after a complete sensitivity analysis.

5.2. Calibration and validation of SWAT model

The observed data obtained is divided into two periods: the first period is used for calibration, and the second period is used for validation, with the necessity that periods of wet and dry years be present in both periods [29]. Using the default values of the model parameters, the model was calibrated automatically using SWAT-CUP and SUFI-2, and the model's performance results were evaluated from the elementary simulations for the streamflow. The results showed that the performance index was less than the permissible limits. Therefore, the parameters were modified based on the sensitivity analysis. In general, calibration and validation of SWAT model are limited by comparison between simulated and observed values of streamflow.

Observed and simulated values of streamflow were drawn as a monthly time step for the calibration for 16 years from January 2000 and validation after that to April 2023 in HD and DD, as shown in Figs. 4 and 7, respectively. For monthly streamflow, the performance of SWAT model at the station of HD shows that R^2, NSE, and Pbs for the calibration (validation) were 0.79, 0.84, and +9.7% (0.89, 0.84, and 7.4%), respectively, whereas at station of DD were 0.87, 0.86, and 5.8% (0.85, 0.83 and −2.5%), respectively. The statistical analysis outcome for streamflow indicates that the model performance is good and reliable in terms of the acceptable standard recommended for Table 2. The results of the statistical analysis also showed a good match with the study results that were conducted for the period 1983–2008, which showed that the values of R^2 at HD for calibration and validation they were 0.93 and 0.74, respectively, while the values of R^2 at the DD for calibration and validation were 0.81 and 0.78, respectively [33,34].

Table 3. Sensitivity parameters for streamflow

Parameter name	Description	Initial range		Fitted value
		Min.	Max.	
CN2	Curve number factor	−0.5	0.5	−0.17
ALPHA_BF	Alpha factor for base flow	0	1	0.65
GW_DELAY	Delay of ground water	30	450	255
ESCO	Factor of soil evaporation	0	1	0.41
GW_REVAP	Groundwater coefficient	0.02	0.2	0.035
HRU_SLP	Mean slope of steepness	0	1	0.65
R_SLSUBBSN	Mean slope length of sub-basin	0	0.02	0.013

Fig. 5 shows the scatter plots between observed and simulated monthly streamflow in station HD; (A) for calibration and (B) for validation. Whereas, Fig. 8 shows the scatter plots between observed and simulated monthly streamflow in station DD; (A) for calibration and (B) for validation.

The total annual streamflow was estimated for HD and DD as shown in Figs. 6 and 9, respectively. The performance of SWAT model in the statistical analysis showed that the R^2, NSE, and Pbs for HD and DD were 0.96, 0.94, and +4.7%, and 0.89, 0.82, and +7.5%, respectively. These values are considered good for the model's performance, which increases the reliability of the results. Furthermore, the average yearly streamflow volume incomes to HD were estimated as simulated and observed, with values of 2.67×10^9 m^3 and 2.60×10^9 m^3, respectively. Similarly, the average yearly streamflow volume income to DD was estimated as simulated and observed, with values of 2.74 billion m^3 and 2.58 billion m^3, respectively. The results obtained indicate a significant decrease in the annual rate of flow when compared with 4.25 and 4.99×10^9 m^3 of entries in DD and HD reservoirs from 1981 to 2008 [35], and 3.76 and 3.95×10^9 m^3 of income in HD and DD reservoirs from 1984 to 2014 [12]. This decrease is was due to the increase in temperature and the decrease in rainfall.

5.3. Assessment water balance in WDR

One of the most significant water balance components in a watershed is SurQ, rainfall, ET, and lateral flow (LatQ) [36], which (except for rainfall) requires good forecasting to measure. Fig. 10 shows the average monthly SurQ and ET values of the water balance components from January 2000 to April 2023. It is noted that SurQ is concentrated from November to May. Also, ET rate is high and increases in the period from March to May. The evaporation process continues from June to

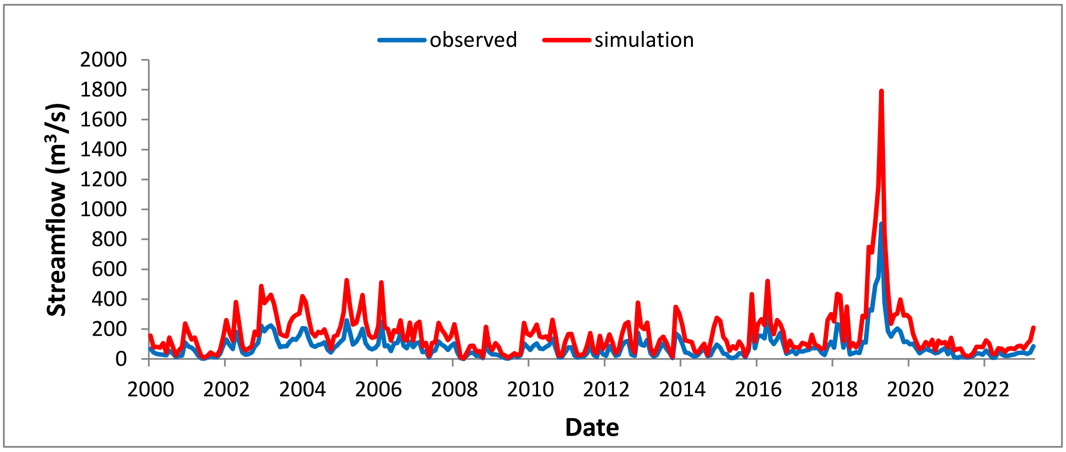

Fig. 4. Average monthly flow between observed and simulated, calibration and validation periods in HD.

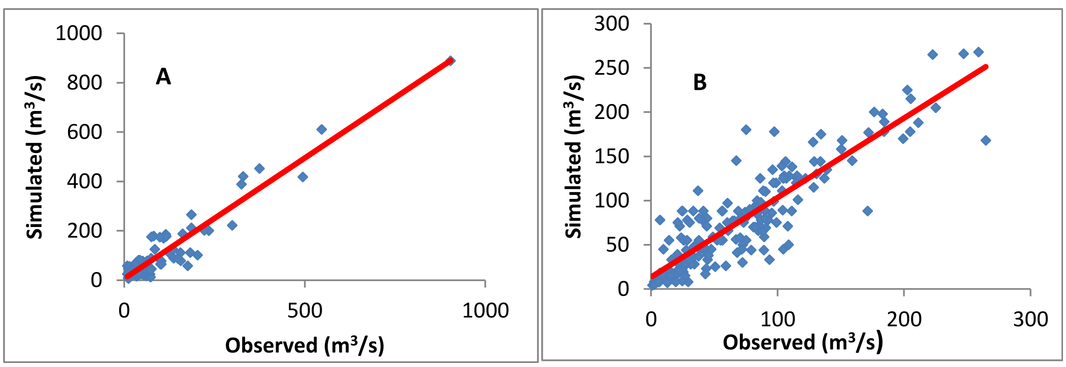

Fig. 5. Scatter plots between observed and simulated monthly streamflow in HD; A) for calibration and B) for validation.

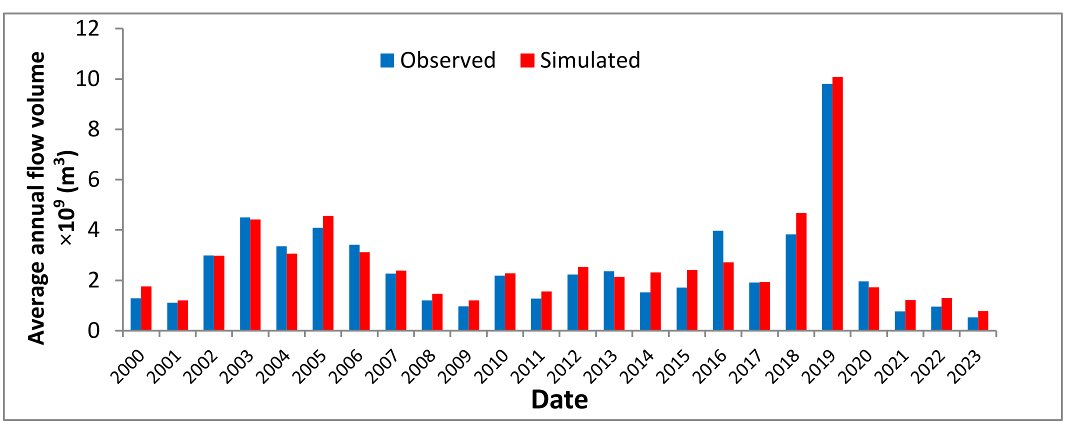

Fig. 6. Average annual flow volume incomes to HD.

September for the soil, despite the lack of rain, but it results from the evaporation of moisture present in the soil due to high temperatures and limited vegetation cover.

According to Table 4 the annual ET rate constitutes 65% of the amount of rainfall in WDR, while the annual flow rate constitutes 37% of the amount of rainfall. These values are consistent with the study conducted on the Hemren catchment area, which showed that the ratio of ET to the amount of rain was 0.68% [33], Therefore, it is possible to reduce the amount of evaporation by planting trees to reduce solar radiation on the soil, as well as to benefit from excess surface water to enhance the

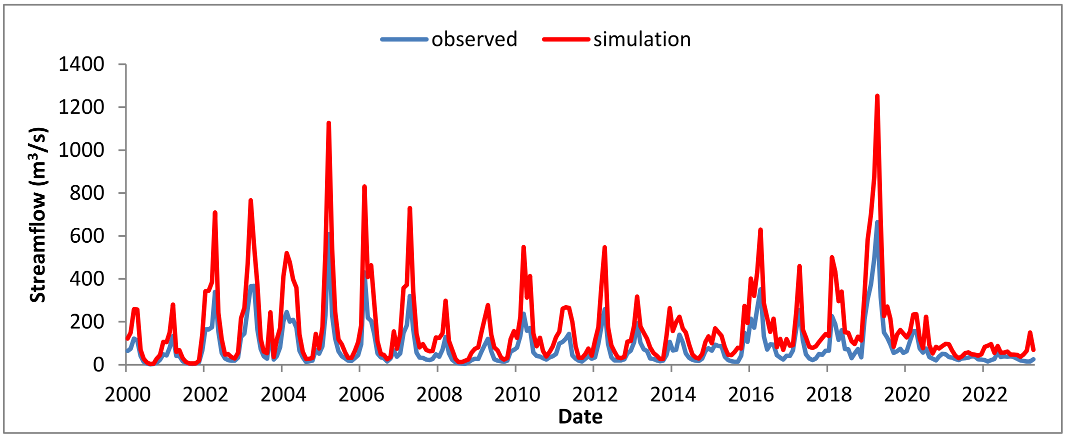

Fig. 7. Average monthly flow between observed and simulated, calibration and validation periods in DD.

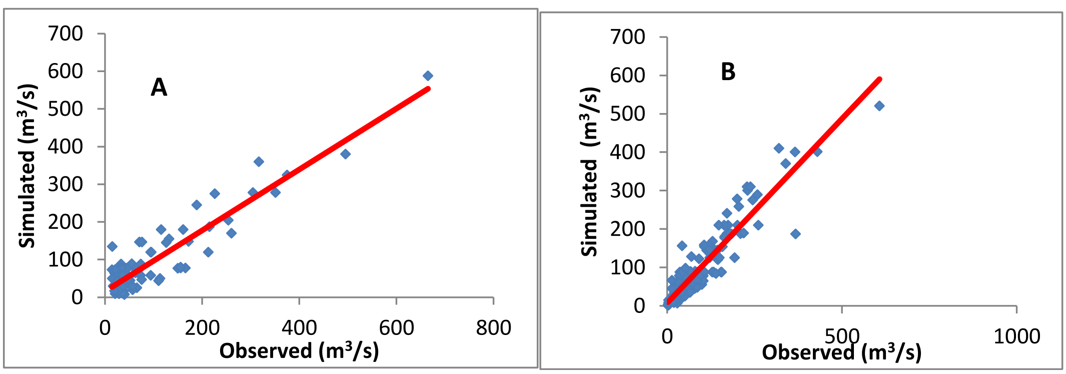

Fig. 8. Scatter plots between observed and simulated monthly streamflow in DD; A) for calibration and B) for validation.

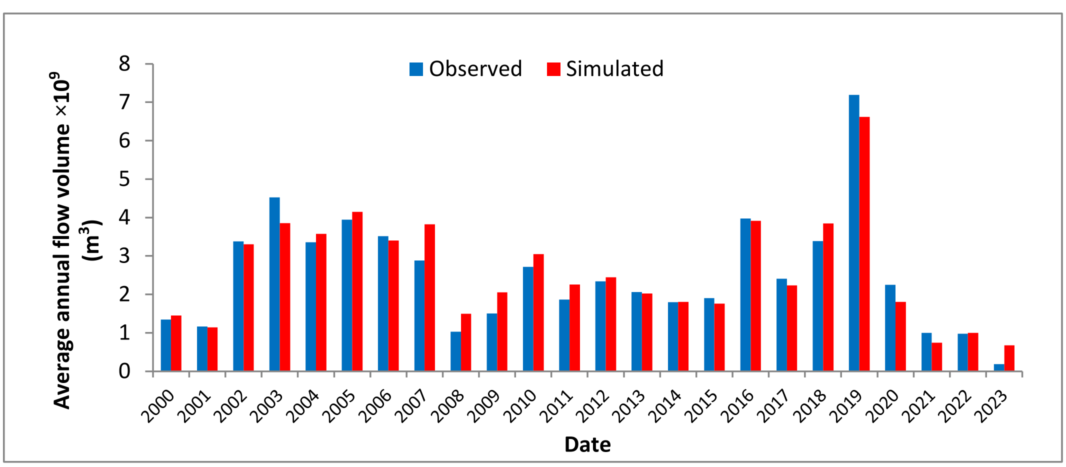

Fig. 9. Average annual flow volume, incomes to DD.

artificial charging of groundwater, especially in the rainy season. On the other hand, LatQ almost does not significantly affect the components of the water balance due to the nature of the soil properties in the region when associated with slopes in the land and a lack of land use, which limits infiltration [36].

5.4. *Assessment of runoff volume in WDR*

The spatial distribution of annual simulated values of SurQ in cubic meters per second was averaged for each sub-basin over the period January 2000 to April 2023, as shown in Fig. 11.

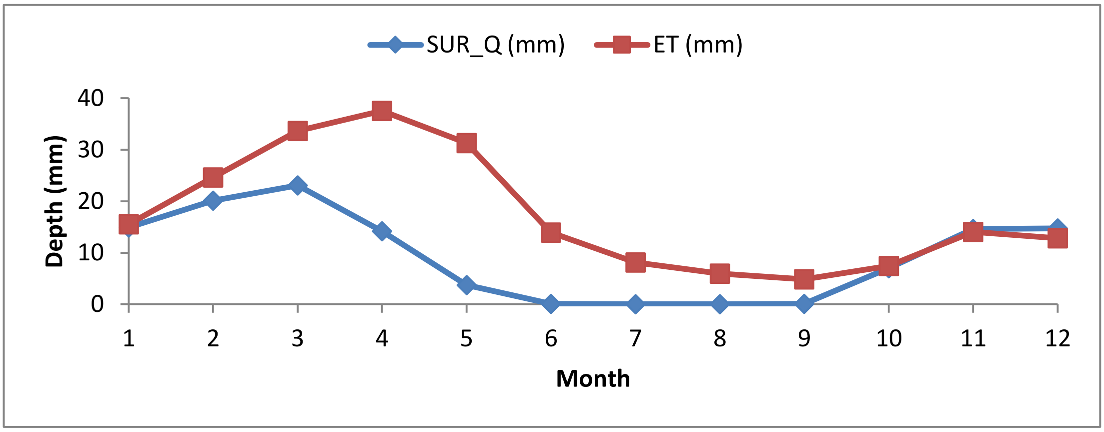

Fig. 10. Average monthly SurQ and ET in the model.

Table 4. Water balance ratio

Details ratio	Values (%)
Stream flow/precipitation	0.37
Base flow/total flow	0.05
Surface runoff/total flow	0.95
Percolation/precipitation	0.02
Deep recharge/precipitation	0
ET/precipitation	0.65

The results illustrated that the annual average SurQ ranged from 320.358 m^3/s to 8.325 m^3/s. It is noted that the amount of SurQ increases in the eastern regions of WDR and gradually decreases towards the west, due to an increase in the amount of rain and the slope of the land. These results are close to the values that were predicted in the same catchment areas, which forecast values between (0.2–539.1) m^3/s from 1983 to 2008 [33,34].

6. Conclusions

In this research, applying hydrological models using SWAT model in WDR, Based on the results obtained when simulating SWAT model from 1996 to April 2023, the most important conclusions were drawn, as follows:

1. The model's performance is considered satisfactory concerning streamflow, as the values of R^2, NSE, and Pbs fell within the acceptable range during calibration and verification of the results. Therefore, the program's outputs can be relied

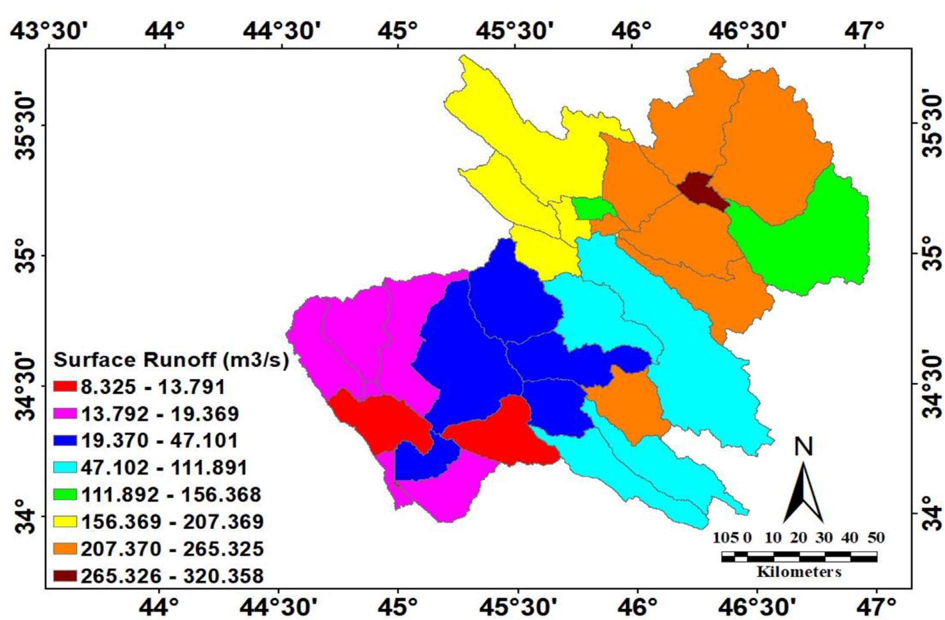

Fig. 11. Average spatial distribution of the annual Surface runoff from 2000 to 2023.

upon to regulate the water management of WDR.
2. Hydrological models can be used to study surface runoff and how it is distributed spatially and temporally in WDR.
3. It is noted that the amount of SurQ increases in the eastern regions of WDR and gradually decreases towards the west, due to an increase in the amount of rain and the slope of the land

We recommend Increasing the number of meteorological stations in the study area, relying on more than one source to provide global meteorological data, cooperating with the Iranian side to exchange hydrological information to achieve the best management of WRD, and including more new sources of data, such as evaporation and discharge gauging along the river's path, which will help increase accuracy in the simulation process and reduce uncertainty.

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Conflict of interest

None declared.

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