Prediction of Surface Runoff for Mosul Dam Reservoir from Different Regional Catchment Areas Using Arc SWAT Model

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Abstract

Due to the lack of surface runoff data in that area, the Mosul dam reservoir watershed was modeled by using the Soil and Water Assessment Tool, which has an interface with the geographical information system (ArcGIS). This model was calibrated for the period extended from 1979–1991 with a monthly intervals and validated for the period from 1992–1999. A SUFI – 2 algorithm procedure within the SWAT-CUP program was applied in the calibration and validation process and sensitivity analysis. The accuracy of this model for the studied area was classified as very good for the calibration period and good for validation according to the statistical parameters. The results of the sensitivity analysis showed that there are eight parameters that have the greatest impact on the hydrological processes in the study area. Results illustrated that the area of the Mosul Dam watershed was 11108 km^2. Results showed that the average annual net runoff that entered the Mosul dam reservoir was 2565 MCM. This represents 13.5% of the average annual total runoff volume. Due to the shortage of water during the dry seasons, this amount is more relevant. As a result, it is necessary to improve the groundwater reservoirs during the rainy seasons and reuse water, as well as increase the effectiveness of water distribution for all uses. Furthermore, the sub-basins in the Iraq region contribute 57.8% of that percentage, 38% of those in Turkey, and 4.2% from sub-basins in Syria.

Introduction

Understanding the behavior and responses of the watersheds requires the use of hydrological models as in Bardossy and Singh (2008). Hydrological modeling is used to illustrate the physical mechanisms that govern the change of precipitation to runoff within a specified catchment area. It improves the perception of a certain portion of the hydrological cycle. The watershed is the first stage that serves as a starting point for addressing problems with the beneficial management of sustainable water resources. Numerous hydrological mechanisms occurring within the watershed should be studied and evaluated in order to meet water resource management challenges. Obviously, the watershed is the main part of this analysis that was performed because all these processes are being implemented within a unique and very small watershed. After understanding these processes, approaches for runoff and land management may be developed scientifically. Numerous hydrologic models with distinct structural features have been created in recent years. Among the different forms of models, semi-distributed models are generally the most effective for hydrological modeling since they circumvent the issues typically experienced with completely distributed models and lumped models, as in (Jajarmizadeh et al., 2013). (SWAT) is one of these models. It is a comprehensive, physically based parameter that requires a lot of input parameters such as soil information, topography, and vegetation nature (Arnold et al., 2012). Its developed by USDA Agriculture Research Service to measure the effect of land management techniques in sizable, complicated watersheds (Gassman et al., 2007). The SWAT model is widely used for hydrologic studies such as assess and predict surface and subsurface flow as stated in (Al- Khafaji et al., 2017; Koltsida et al., 2021; Mahratta et al., 2021), evaluation of climate change on stream flow as in (Abbasa et al., 2016; Abbasa et al., 2018; Al Hillo et al., 2019), and identification of water quality including nutrient loading,

total daily maximum loads, pesticides and bacteria (Gassman et al., 2014; Shinde et al., 2017). The SWAT hydrological model can be used not just in dry areas, but also in semi-arid and moist areas such as India Li and Fang (2021), Tunisia (Hemrassi et al., 2017) and Ghana as in (Samuel et al., 2020), and Laos (Vilaysane et al., 2015).

Iraq's water supplies have declined dramatically in recent decades. Several reasons have contributed to Iraq's water scarcity crisis, including the water policies of neighboring countries, recent climate changes, and mismanagement of the water resources in the country. Iraq's water supplies have declined dramatically in recent decades. Several reasons have contributed to Iraq's water scarcity crisis, including the water policies of neighboring countries, recent climate changes, and poor management of the country's water resources. This type of mismanagement faces a number of problems, such as an increase in the need for water due to rapid population growth, a high level of sediment in the rivers, and the neglect of sanitation systems, which causes waste water to be mixed with rainwater and then dumped directly into rivers, polluting them and lowering their quality (Al Hadithi et al., 2020).

So far, no study has been conducted on hydrological models to better understand water balance components in the reservoir of Mosul dam catchment area. As a result, this study will provide a clear picture of the hydrological response in the Mosul dam watershed. The main objective of this study were (1) quantification of the water balance component of Mosul dam watershed, (2) simulation of hydrologic processes of Mosul dam watershed by using SWAT model, and (3) assessment of the contribution ratio of each country (Iraq, Turkey, and Syria) within the Mosul dam watershed to runoff that enters the Mosul dam reservoir in any case of Tigris River discharge at the Cizre gauge station (upstream Mosul Dam watershed).

Material And Methods

Study Area

The Tigris River is 1800 kilometers long and originates in the Taurus Mountains of eastern Turkey, around 25 kilometers southeast of Elazig and about 30 kilometers from the headwaters of the Euphrates. The Tigris river watershed above Mosul dam is approximately 54,300 km^2 in size and is divided into three sections (AL – Madhhachi et al.,2021), as shown in Fig. 1: the upper section is located upstream of the Illisu dam, the middle section is located between Illisu and the proposed Cizre dam, and the lower section is located between Cizre and Mosul dam. As seen in Fig. 1, the emphasis of this study was on the lower portion of the region extending inside the Iraq-Turkey-Syria boundaries from 36°35 20 to 37º48 00 N and 41º46 33 to 43º29 17 E. The Mosul Dam is Iraq's biggest dam. It is 52 kilometers upstream from the city of Mosul on the Tigris, in the western province of Nineveh (AL – Madhhachi et al., 2021). The main purposes of dam are to store the excess water through the flood, irrigation, and hydropower generation.

The annual production of electrical power was (1060 MW) as stated in [https://ar.wikipedia.org/wikiMosul dam] and the historical records of discharge into the dam showed that the maximum, minimum, mean monthly inflow for the period 2000–2019 was about 2881,77,477 m^3/sec, respectively. In addition, the annual precipitation was ranged between 147 to 640mm (MOWR. 2022). The main resources of water to the Mosul dam watershed are divided into three parts, namely, stream flow, ground water flow, and surface flow generated from precipitation.

Swat Model Description

Commonly used to estimate the effects of changes in land use and land management on water quantity and water quality is the Soil Water Assessment Tool (SWAT) watershed model as in (Arnold et al., 1998). The SWAT model simulates watershed processes on a daily time scale, including hydrology, soil erosion, crop development, and biogeochemical cycles on the land and in the stream network. The model is linked geographically to a particular watershed or sub-watershed. The hydrologic response units (HRUs), which typically have similar soil type, land use, and slopes, are the smallest geographical units in the model. The water budget equation, which is as follows, served as the fundamental equation for the hydrologic cycle in the SWAT Model.

$SW_t = SWo + \sum_1^t (R_{day} - Q_S - E_a - W_S - Q_{gw})$ (1)

Where SW_t represents the water content of soil in (mm), SWo represents the initial water content in soil (mm), t the time (day), R_{day} is the daily rainfall in (mm), Qs represents the surface runoff (mm), Ea the evapotranspiration (mm), Ws represents the water stored in vadose (mm), and Qg The amount of water returning from the ground to the surface (mm)

Swat Input Data

Input data for swat model are discussed as follows:

1-Digital elevation model (DEM) was used in this research with a spatial resolution of 30m (1 – acre – second) Shuttle Radar Topography Mission (SRTM) version 3.0, as shown in Fig. 2 to delineate Mosul dam watershed, streams extraction, and calculation of sub-basins with respect to the method of DEM – based provided by watershed delineation window in SWAT2012. The SRTM was loaded from (https://portal.opentopography.org.) website during June 2022 as a tif format at geographic system, then was projected to the UTM coordinate system. The catchment area was 11108 km^2 which was distributed with a percentage of 48% in Iraq, 44% in Turkey, and 8% in Syria.

2- A soil classification map of the research region was constructed using the worldwide soil dataset of the Food and Agriculture Organization of the United Nations soil classification system (Fao, 1995), which provides data for more than five thousand varieties of soil at a geographical scale of one to five million.

Different hydrological processes are greatly impacted by soil type in watershed modeling. Numerous soil parameters, such as soil texture, accessible water content, bulk density, organic carbon content, and hydraulic conductivity, were included in the FAO-UNESCO soil classification (Fao, 1995). To enter these attributes into the ArcSWAT2012 model for modeling purposes, however, they must first be assessed. In this study, the soil of the Mosul Dam watershed was categorized as loam, clay loam, and clay soil with a percent of 48.77%, 16.85%, and 34.38% of the total watershed area, as shown in Fig. 3.

3- Land use/land cover map was downloaded from the United State Geological Surveys website (https://earthexplorer.usgs.gov.) during the period of 1996 based on Landsat8 satellite with a spatial resolution of 30m. The watershed of Mosul dam has been seven classes of land cover as illustrated in Fig. 4 based on Maximum Likelihood Technique of supervised classification method with an overall accuracy of 86%. The areas of the LU/LC coverage the watershed of Mosul dam are shown in Table 1.

Table 1
Area of each lu/lc classification within the studied watershed

Land use classification	ArcSWAT Codes	% of watershed area	Area(Km^2)
Forest land – mixed	FRST	11.89	1320.98
Pasture Land	PAST	39.55	4394
Agriculture land- Row crop	AGRR	0.47	52.22
Agriculture land-generic	AGRL	18.56	2062.02
Barren land	BARR	26.40	2933.04
Urban land	URBN	0.77	85.55
Water	WATR	2.36	262.2

4-The surface slope is the major inertial generating component for overland flow (Khayyun et al., 2020). The Hydrologic Response Units (HRUs) were then generated using five intervals of surface slope classifications, ranging from 0–10%, 10–20%, 20–30%, 30–40%, and more than 40%. Figure 5 illustrates how the surface slope map of the catchment region was presented.

5- Weather data represented by rainfall, maximum and minimum temperature, solar radiation, wind speed, and relative humidity that utilized in SWAT model for runoff simulation purposes were provided from Climate Forecasting System Reanalysis (CFSR). Daily scale data was downloaded from the website (http://globalweather.tamu.edu/). These data showed an agreement results when compared with the Mosul metrological data as in Mohsen (2020). Figure 6 shows the distribution of weather stations which were used in SWAT Model.

6- Monthly inflow at Mosul stream flow station was collected from two sources; the data series number 540 from the United States Geological Survey (USGS), as shown in Saleh (2010), and Al Dabbagh (2021). The average monthly flow at Cizre gauge station (upstream Mosul watershed) were used as inlet

discharge to this watershed in Swat model. The average annual discharge as stated in Emrah (2010) was 1147 m^3/sec as illustrated in Table 2.

Table 2
Average monthly inflow at Cizre gauge station for period (1979–1999)

Month	Inflow (m^3/sec)	Month	Inflow (m^3/sec)
Jan.	948	**Jul.**	547
Feb.	1416	**Aug.**	366
Mar.	2013	**Sep.**	354
Apr.	2813	**Oct.**	366
May.	2253	**Nov.**	629
Jun.	1037	**Dec.**	1024

Setup Of Model

The Soil and Water Assessment Tool model of the Mosul dam catchment area was built using three separate layers: 30 SRTM DTM, LU/LC, and type of soil layers. As a result, the study area was divided into twenty sub-catchments with an area ranged from 4.88 to 3544.35 Km^2, as illustrated in Fig. 7. A multiple HRU definition was used to better depict the research area's heterogeneities in soil, land use, and terrain. Finally, 462 HRUs were constructed for the entire watershed. The Penman-Monteith approach was utilized in the simulation procedure to determine evapotranspiration, and the method of variable storage variable storage was used for routing of the stream flow as in stated in (Al-Khafaji et al., 2017).

Evaluation Criteria

The four statistical criteria, namely, Nash-Sutcliffe efficiency (N_{SE}), the Root Mean Square Error (RMSE) to the standard deviation of observed data (STDobs) ratio (RSR), the percent bias (Pbias), and coefficient of determination(R^2) were used to assess the accuracy of the Soil and Water Assessment Tool model simulation of the Mosul dam reservoir basin.

The Nash-Sutcliffe efficiency measures the variation of measured data versus modeled data in comparison to a 1:1 best fit line; the NS_E value varies from ($-\infty$) to 1, with any NS_E values higher than or equal to 0 indicating that the modeled value predicted the component of consideration more accurately than the mean measured value, and an N_{SE} value of 1 indicating ideal modeling. The following equation was used to compute the NS_E values:

$$N_{SE} = 1 - \frac{\sum_{i=1}^{N}(Q_i - M_i)^2}{\sum_{i=1}^{N}(Q_i - Q_a)^2} \quad (2)$$

where Q_i and M_i are the observed and simulated stream flow values for the ith pair of stream flow values, respectively. Q_a is the mean value of the measured stream flow values, and N is the total number of paired stream flow values.

Root mean square error to the standard deviation of observed data ratio is an error criteria statistics. The simulation will accept when the value of RSR is less than 0.5. the following equation was used to calculate the RSR values:

$$RSR = \frac{RMSE}{STD_{ob}} = \frac{\sqrt{\sum_{i=1}^{N}(Q_i - M_i)^2}}{\sqrt{\sum_{i=1}^{N}(Q_i - Q_a)^2}} \quad (3)$$

The percent bias test indicates if the mean trend of the modeled data is greater or less than the measured data. Any nugatory P_{bias} values state that the modeled data is, on average, larger than the measured data. On the other hand, any values greater than zero states that the modeled data is less than the measured data on average. The simulation will be typical if P_{bias} is equal to 0. The P_{bias} values were derived using the following equation:

$$P_{bias} = \frac{\sum_{i=1}^{N}(Q_i - M_i)}{\sum_{i=1}^{N} Q_i} \quad (4)$$

According to the proportion of whole variation described by the model, the coefficient of determination (R^2) shows how well the model was able to predict events based on how much of the total variation it explained. R^2 values vary from 0 to 1, with improved model performance as the value of R^2 approaches 1. Using the following equation, R^2 values were calculated:

$$R^2 = \frac{\left[\sum_{i=1}^{N}(Q_i - Q_a)(M_i - M_a)\right]^2}{\sum_{i=1}^{N}(Q_i - Q_a)^2 \sum_{i=1}^{N}(M_i - M_a)^2} \quad (5)$$

Where M_a is the mean value of modeled stream flow .

Results And Discussion

Sensitivity Analysis

Twenty-five hydrological parameters were investigated to characterize the sensitive parameters for the stream flow simulation of the Mosul reservoir dam watershed. To achieve this process, a semi-automated

global search procedure that is called the Sequential Uncertainty Fitting version 2 (SUFI2) algorithm within the SWAT calibration and uncertainty program that was developed by Abbaspour (2004, 2007) was applied. According to statistical parameter value (i.e., p-value and t-stat value), eight hydrological parameters were found to be the most sensitive parameters to the calibration of the Mosul Dam reservoir watershed model as shown in Table 3. Parameters were considered as a substantially sensitive when the P – value less than 0.1. These parameters were (CN) curve number factor, (ALPHA_BNK) Baseflow alpha factor for bank storage, (CH_K2) Effective hydraulic conductivity in main channel alluvium, (CH_N2) Manning's "n" value for the main channel, (SOL_k) Saturated hydraulic conductivity, (Timp) Snow pack temperature lag factor, (GWQMN) Threshold depth of water in the shallow aquifer required for return flow to occur, and (GW_DELAY) Groundwater delay.

Table (3): sensitivity analysis of Mosul dam reservoir watershed Model parameters for calibration of runoff.

Parameter	Mosul	P - Value	t- value	Initial values	Final values	Fitted value
CN2	1	0.00	-44.01	-0.6–0.6	-0.784–0.083	-0.29
ALPHA_BNK	2	0.00	-11.60	0.1–0.9	0.23 - 0.66	0.503
CH_K2	3	0.00	5.08	-0.01-150	115.24- 155.62	139.5
CH_N2	4	0.00	4.20	0.05–0.25	0.084 - 0.28	0.191
SOL_k(..)	5	0.01	2.48	-0.2- 0.3	-0.13 - 0.45	0.28
TIMP	6	0.01	2.46	0–0.6	0.00 – 0.15	0.039
GWQMN	7	0.07	-1.82	30–150	151.00-350.56	309.65
GW_DELAY	8	0.08	1.76	30–450	50.97 - 100.60	97.38
RCHRG_DP	9	0.10	1.62	0–0.2	0.13–0.19	0.183
GW_REVAP	10	0.34	-0.94	0.02–0.15	0.16–0.197	0.190
SOL_AWC(..)	11	0.37	0.88	0.1–1	0.338 - 0.61	0.615
SLSUBBSN	12	0.41	0.80	20–70	1.24 - 77.45	45.93
OV_N	13	0.53	-0.61	0.05–0.6	0.31 - 0.56	0.51
SURLAG	14	0.5	0.55	0.1–20	11.51 - 16.86	12.25
EPCO	15	0.58	0.55	0.05–0.8	0.52 - 0.89	0.67
ALPHA_BF	16	0.59	0.53	0–1	0.12 - 0.87	0.86
SMFMN	17	0.66	-0.43	0–8	5.43 - 11.23	6.08
TLAPS	18	0.67	0.41	-5–6	3.98 - 6.63	6.60
REVAPMN	19	0.82	0.21	10–150	3.05 - 55.45	55.11
SFTMP	20	0.84	0.20	-5–5	2.41 - 15.24	9.39
SOL_BD(..)	21	0.94	0.07	0.9–2	1.26–2.50	1.81
HRU_SLP	22	0.94	-0.06	0.1–0.7	0.47 - 0.82	0.53
ESCO	23	0.94	-0.06	0.1–0.96	0.17 - 0.74	0.40
SMTMP	24	0.95	0.06	-5–5	5.37 - 13.54	13.03
SMFMX	25	0.97	0.02	0–10	13.80 - 16.92	16.45

Calibration, Validation, And Model Performance

Monthly observed streamflow data collected at the guage station of the Mosul Dam reservoir basin from 1979 to 1999 were used to calibrate and validate the SWAT model. The measured streamflow data for period 1979–1991 were used for calibration and for validation process, the period 1992–1999 were used. In the calibration process, the SWAT-CUP program was run many times with 700 simulations for each iteration. The ranges of calibrated parameters were chosen from the final iteration as demonstrated in Table 3 and applied in the validation process without any change in these ranges and with the same number of simulations. Figure 8 shows the time series of the measured and simulated streamflow for the calibration and validation period. The relationship between measured and modeled stream flow for two distinct time periods as illustrated in Fig. 9 and Fig. 10.

To assess the accuracy of the SWAT model for the Mosul dam reservoir watershed, the statistical parameters that were recommended by Moriasi et al. (2007) were used. These parameters have been determined for two periods as illustrated in Table 4. According to the values of these parameters, the accuracy of Mosul dam reservoir catchment model was classified as very good for the calibration period, while the performance for the validation process was classified as good for the value of $N_{SE,}$ RSR, and P_{bias} parameters and very good according to coefficient of determination R^2.

Table 4
Statistical parameter for calibration and validation periods

period	N_{SE}	R^2	RSR	P_{bias} (%)
Calibration period (1979–1991)	0.86	0.86	0.37	-0.3
Validation period (1992–1999)	0.74	0.78	0.51	14.4

For the twenty-one years of simulation, The water balance variables were estimated using the main and modified SWAT model parameters based on Eq. (1); the water balance ratio estimates are shown in Table 5.

Table 5
simulation of water balance components by SWAT model.

Component ratio	Primary simulation	Calibrated simulation
Streamflow/precipitation	0.52	0.39
Baseflow/total flow	0.34	0.12
Surface runoff/total flow	0.66	0.88
Percolation/precipitation	0.19	0.31
Deep recharge/ precipitation	0.01	0.06
Evapotranspiration/precipitation	0.46	0.36

Consequently, in the absence of the stream flow data from the Tigris river at the Cizre gauge station upstream the studied watershed, the surface runoff has been determined by operating the SWAT model for twenty-one years and changing the variables in the SWAT model application databases to the best fit variable values of the most recent iteration as a result of SWAT-CUP calibration. Results showed that the average annual surface runoff that entering to the Mosul dam reservoir was 2565 MCM. This represents 13.5% of the average annual total runoff volume (runoff from Mosul dam watershed and the streamflow of Tigris river at Cizre gauge station). The sub-basins in the Iraq region contribute with 57.8% of that percentage, 38% from those in Turkey, and 4.2% from sub-basins in Syria. The Annual runoff from sub – basins within the watershed for period (1979–1999) as shown in Fig. 11

Conclusions And Recommendations

In this study, the watershed of Mosul dam reservoir was analyzed hydrologically by using the semi-distributed physical model; ArcSWAT 2012; with an interface with Arc GIS software. This area was chosen due to the absence of information about surface runoff in it. According to the results from calibration and sensitivity analysis processes, the most sensitive parameters were (CN), (ALPHA_BNK), (CH_K2), (CH_N2), (SOL_k), (Timp), (GWQMN), and (GW_DELAY) depending on the P and t values. The accuracy of the SWAT model was categorized as very good for the calibration period for all statistical parameters; good for the validation period for the statistical parameters (NSE, RSR, and Pbias); and very good for the R^2 parameter. Evapotranspiration has a considerable impact on the surface runoff from the basin, where 36% of the precipitation is dissipated. Results showed that the average annual net surface runoff that entering to the Mosul dam basin was 2565 MCM. This represents 13.5% of the average annual total runoff volume (runoff from Mosul dam watershed and the streamflow of Tigris river at Cizre gauge station upstream the watershed). This amount is more significant due to water scarcity in dry seasons. additionally, the sub-basins in the Iraq region contribute with 57.8% of that percentage, 38% from those in Turkey, and 4.2% from sub-basins in Syria. The study's findings are very valuable for water resource planning and management in Iraq with regard of water availability and sustainability.

Finally, there are several recommendations necessary to fill the shortage of water resources within the dry seasons or as a results of negative global climate change that affects rainfall and consequently on water resources, as well as: Development the traditional water resources, which includes enhancing storage in underground water reservoirs, Increasing the efficiency of water distribution networks for all uses, and the utilization of non-traditional water resources of all kinds, including the reuse of sewage, industrial and agricultural waters.

Declarations

Author Contributions:

Methodology, Nasser Kh. Muhaisin and Thair, S., Khayyun; visualization, Nasser Kh. Muhaisin; supervision; Thair, S., Khayyun and Mustafa M., Al mukhtar, resources, Nasser Kh. Muhaisin, All authors

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All data of this manuscript are discussed at section Materials and Method.

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Figures

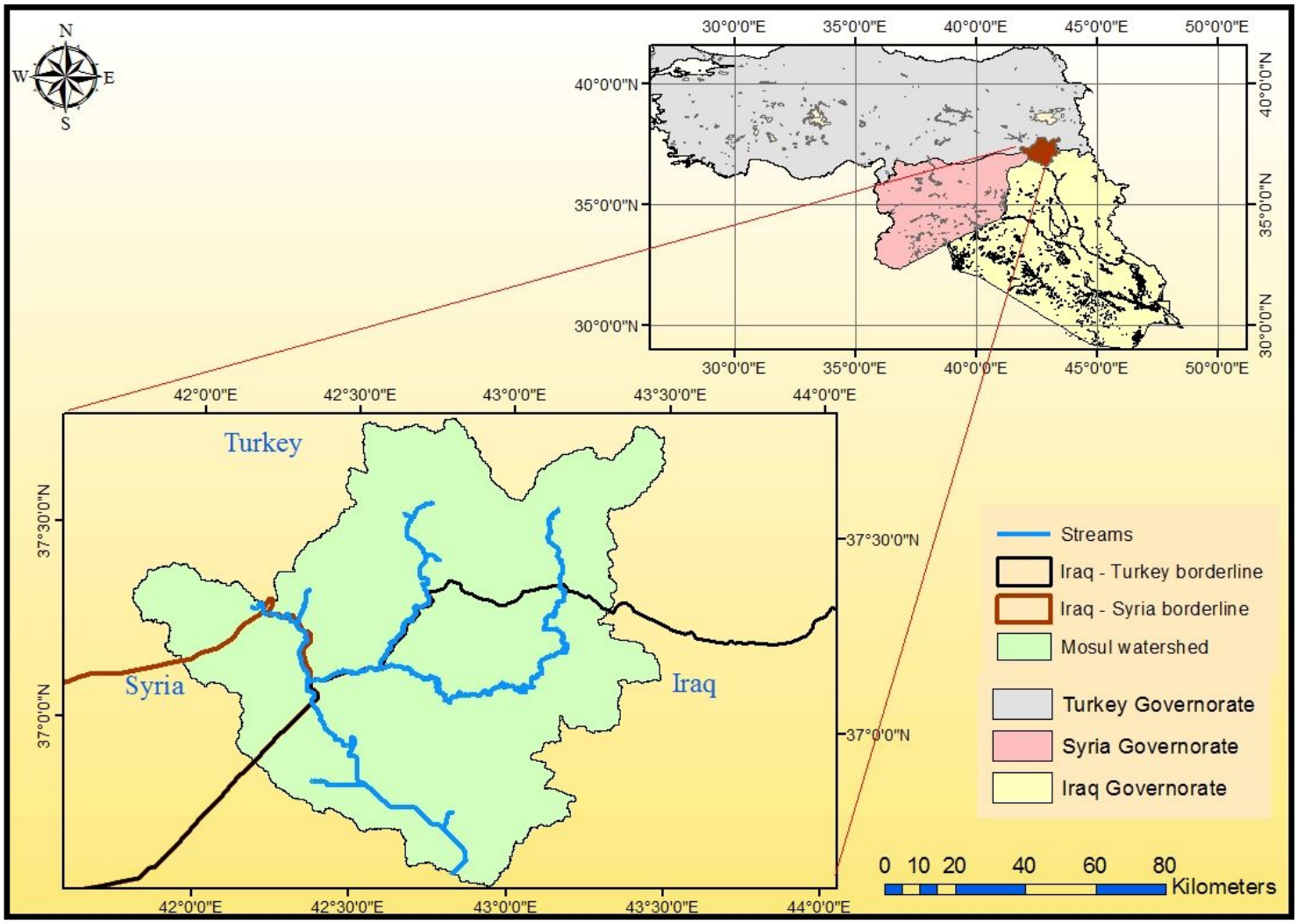

Figure 1

Location of Mosul Dam Watershed

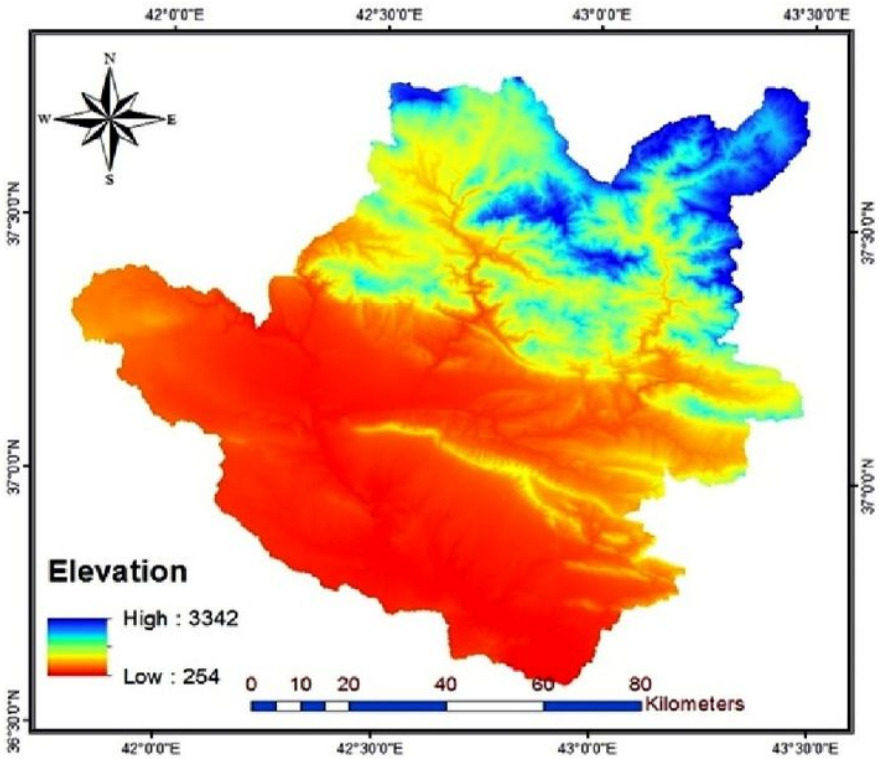

Figure 2

Digital elevation map for Mosul dam watershed

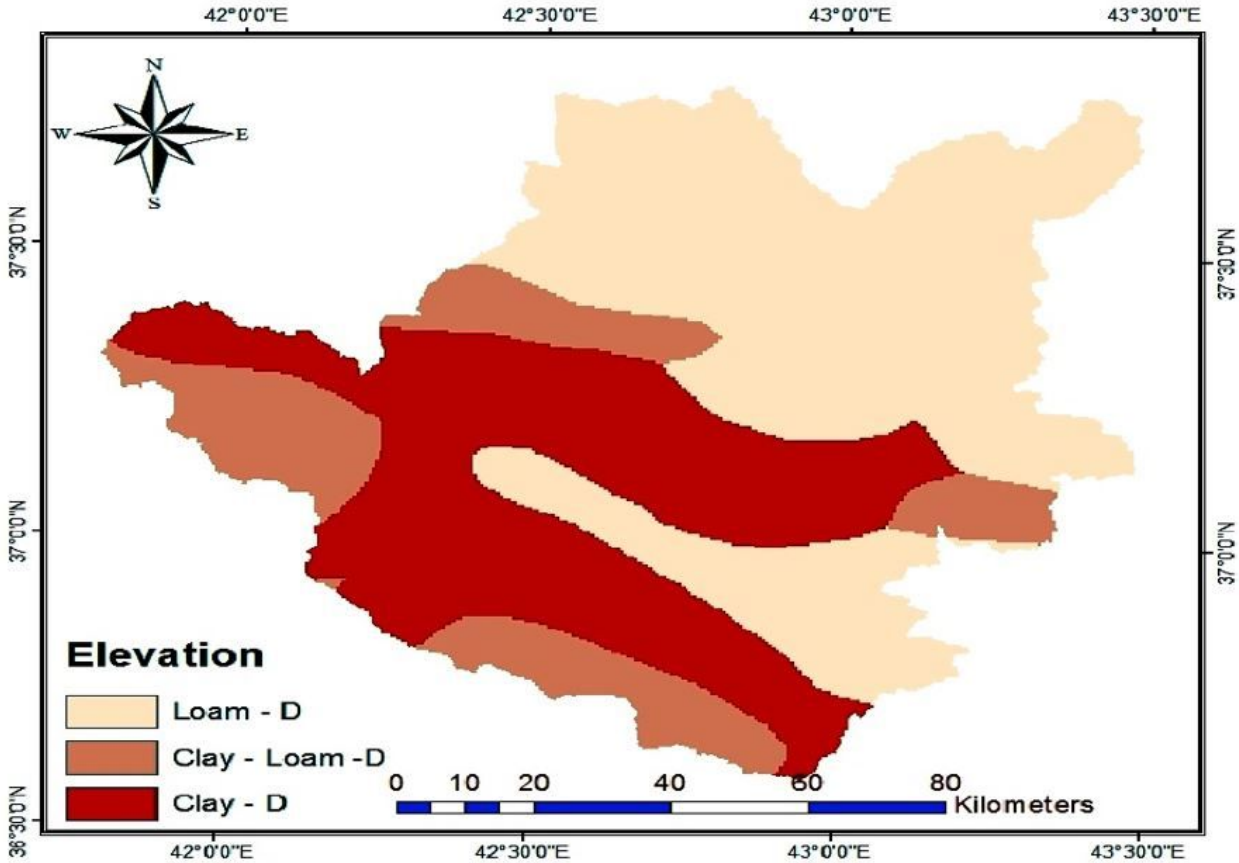

Figure 3

Soil classification of Mosul dam watershed

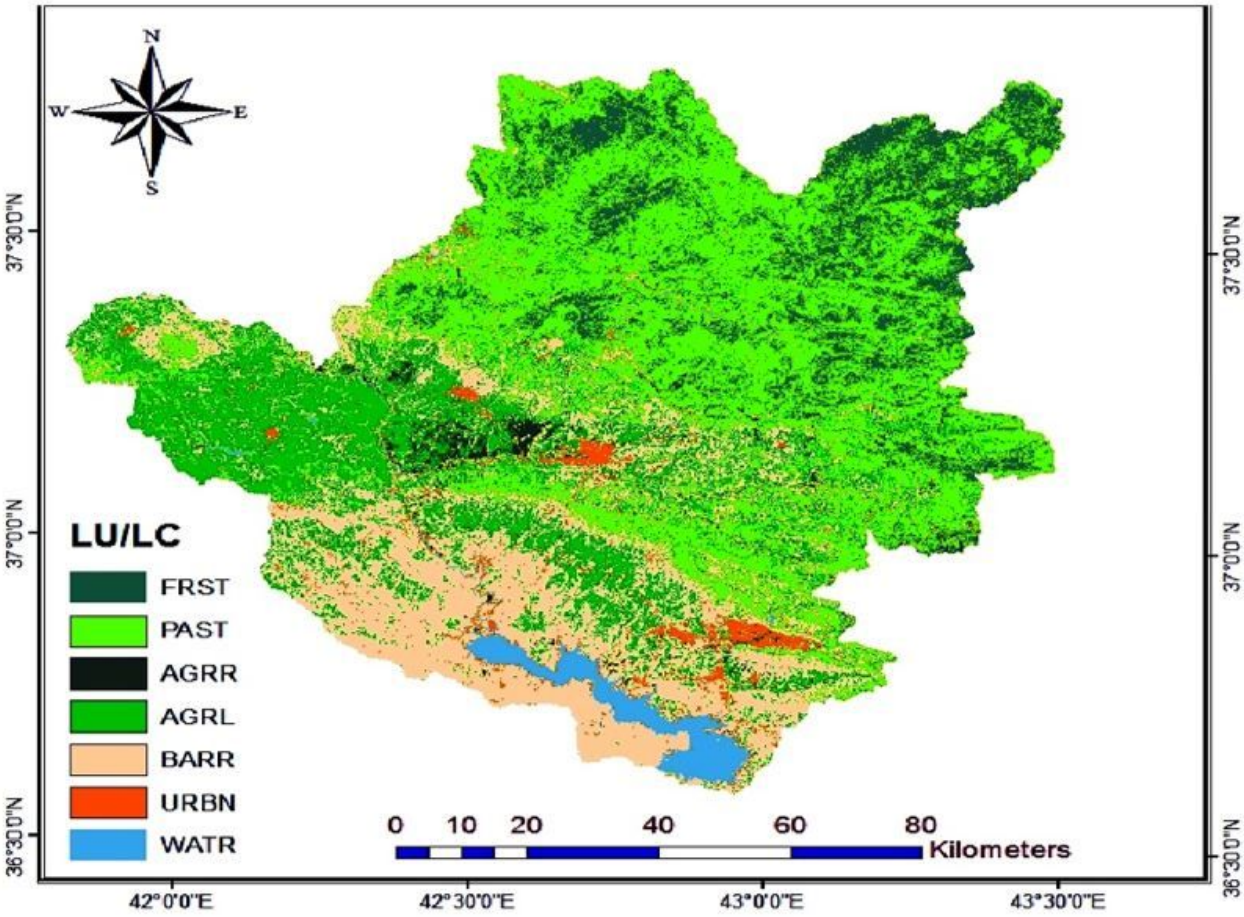

Figure 4

LU/LC map of Mosul dam watershed.

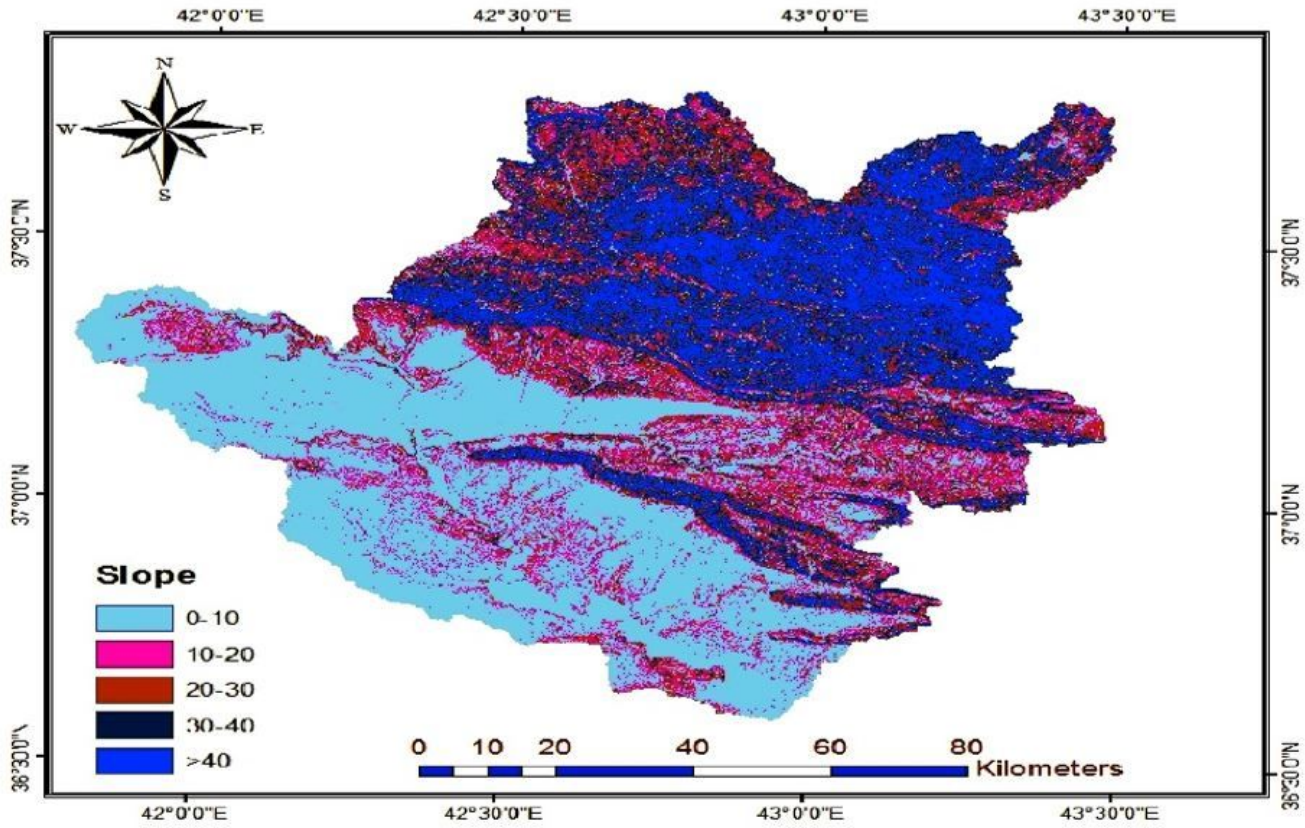

Figure 5

Slope map of Mosul dam watershed.

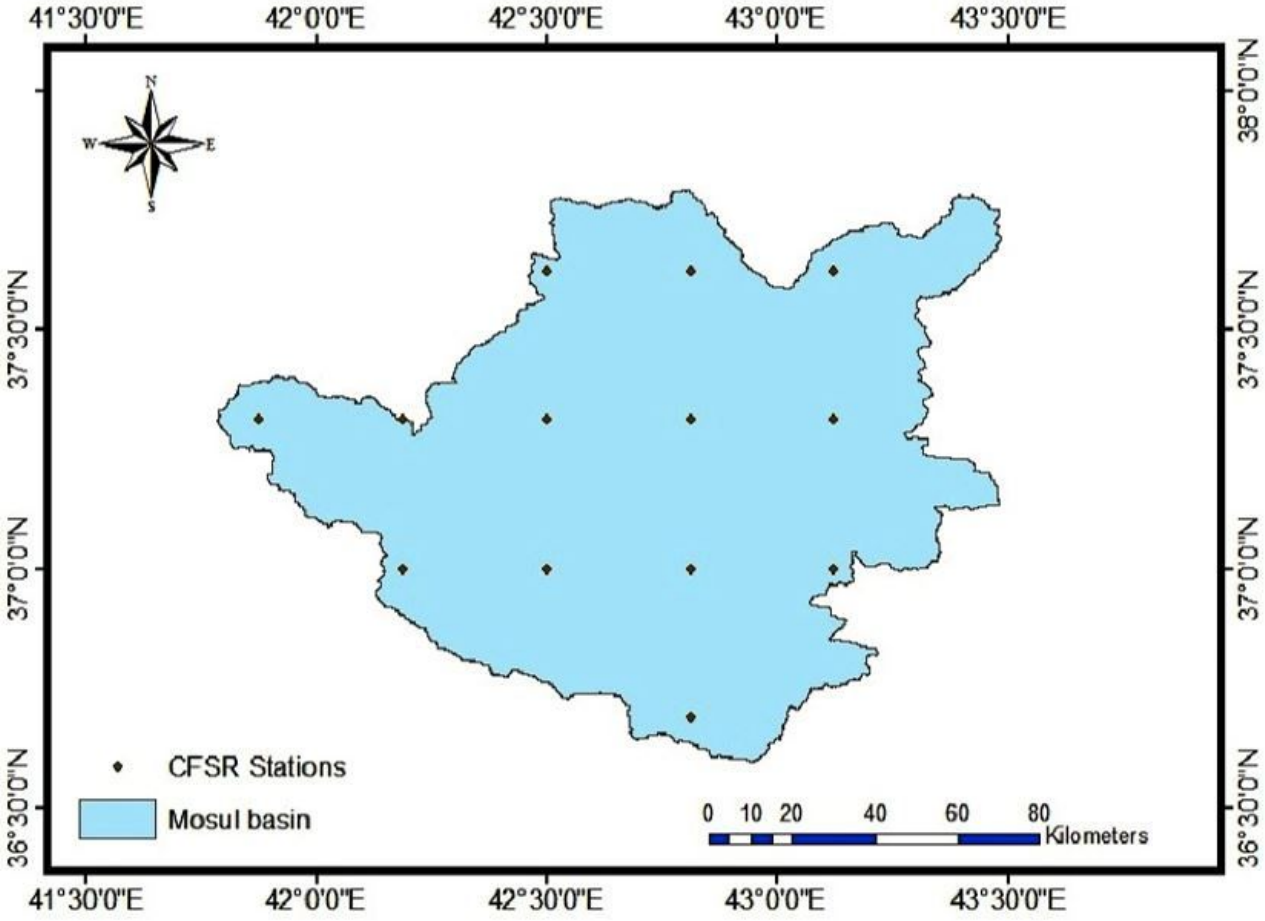

Figure 6

Distribution of CFSR weather station at Mosul watershed

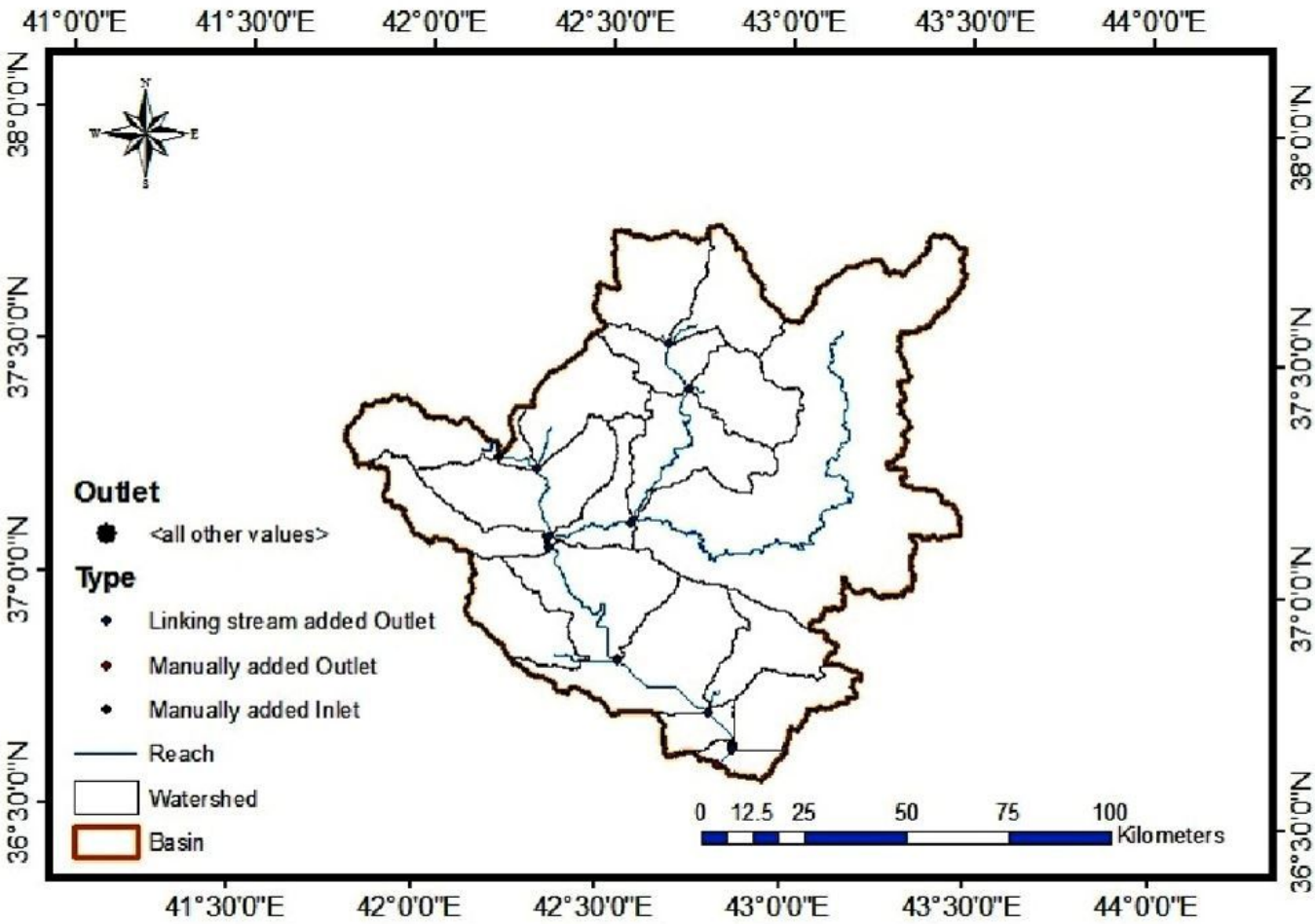

Figure 7

Delineation of Mosul dam reservoir watershed.

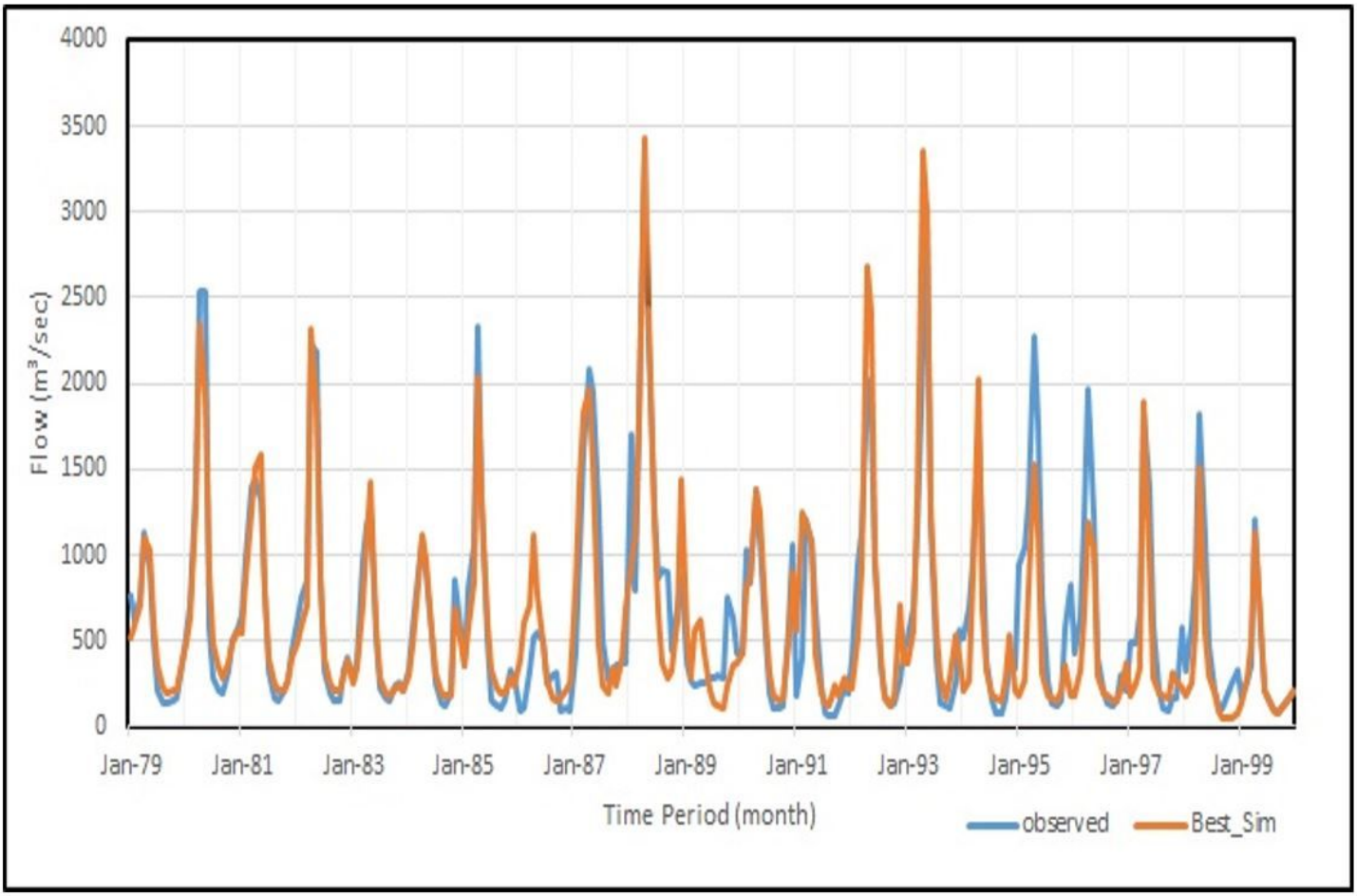

Figure 8

Time series of observed and modeled streamflow in Mosul basin.

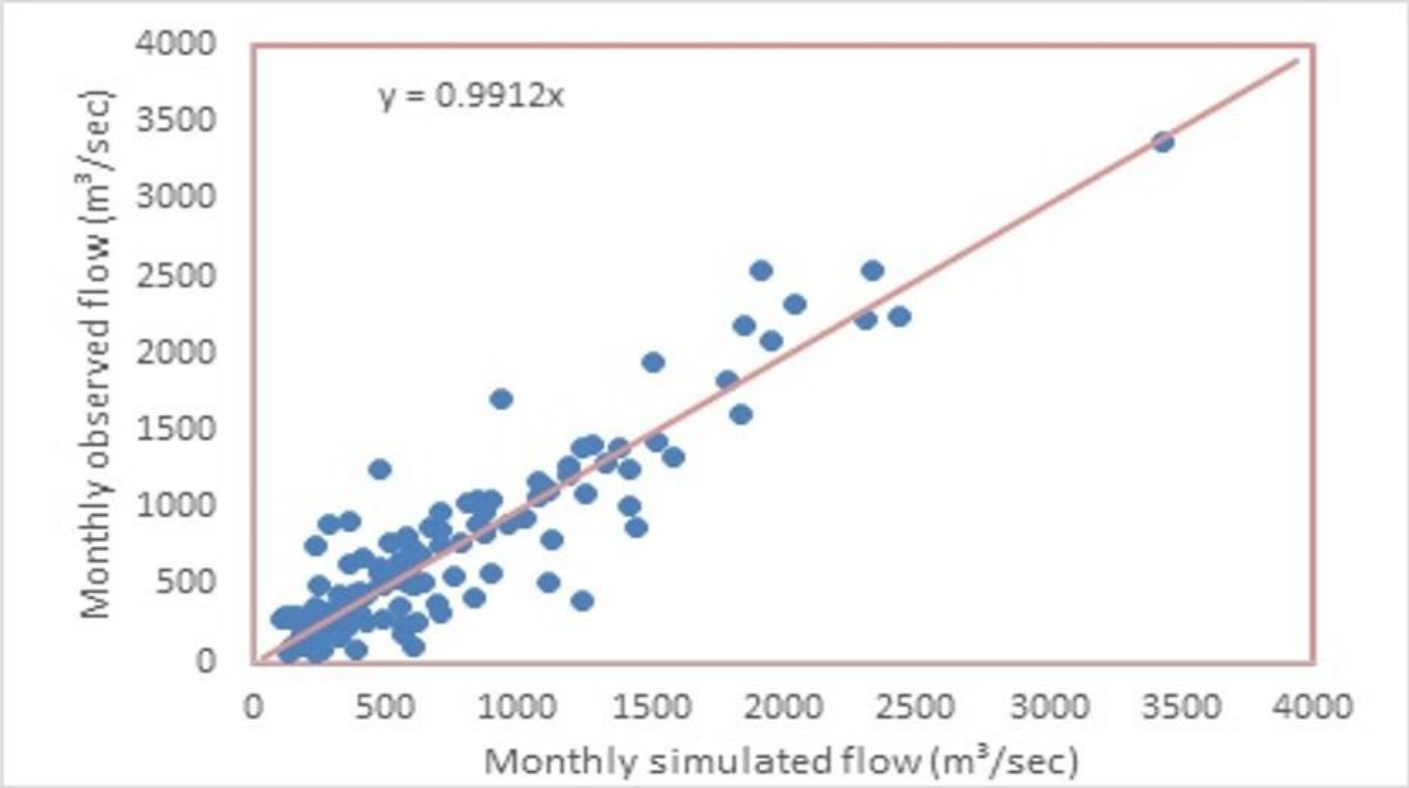

Figure 9

Relationship between measured and modeled stream flow for calibration period

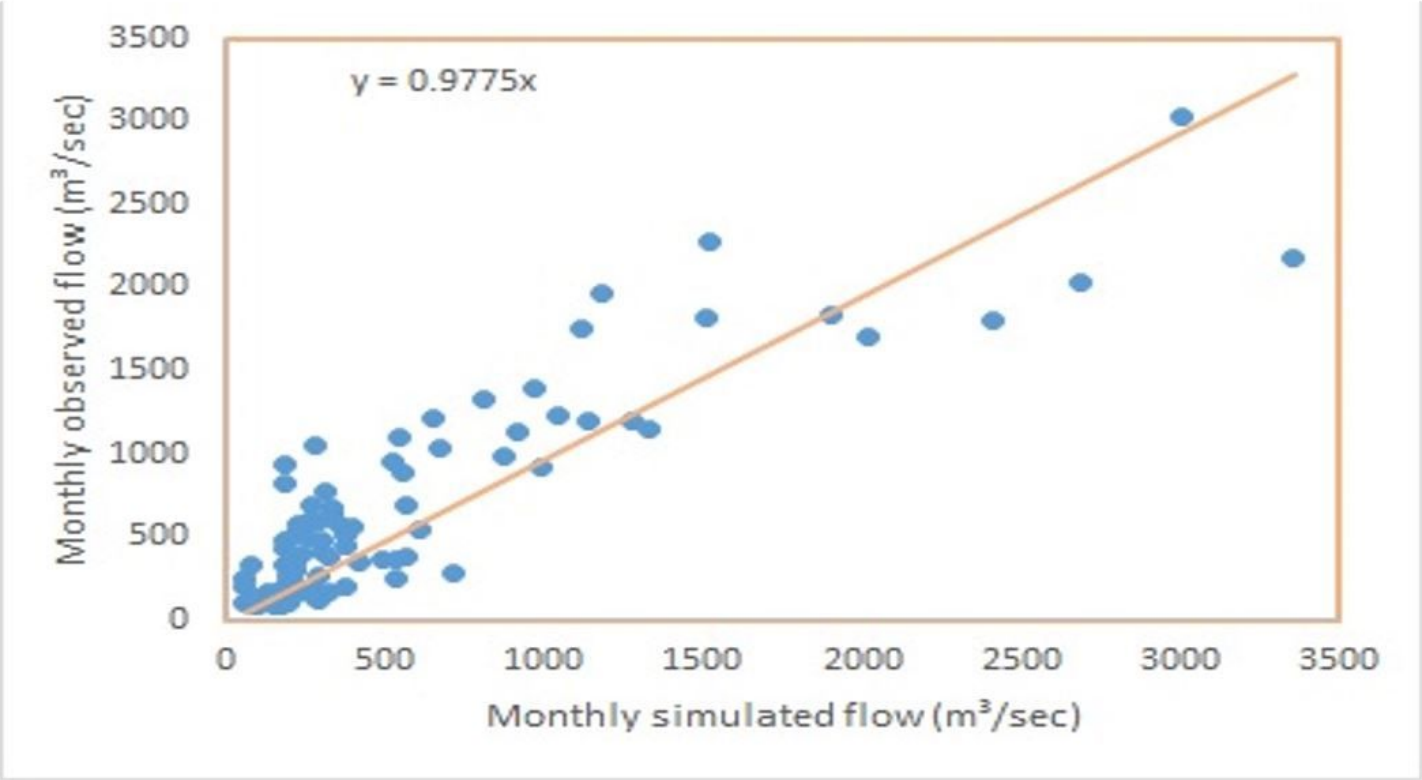

Figure 10

Relationship between measured and modeled stream flow for validation period

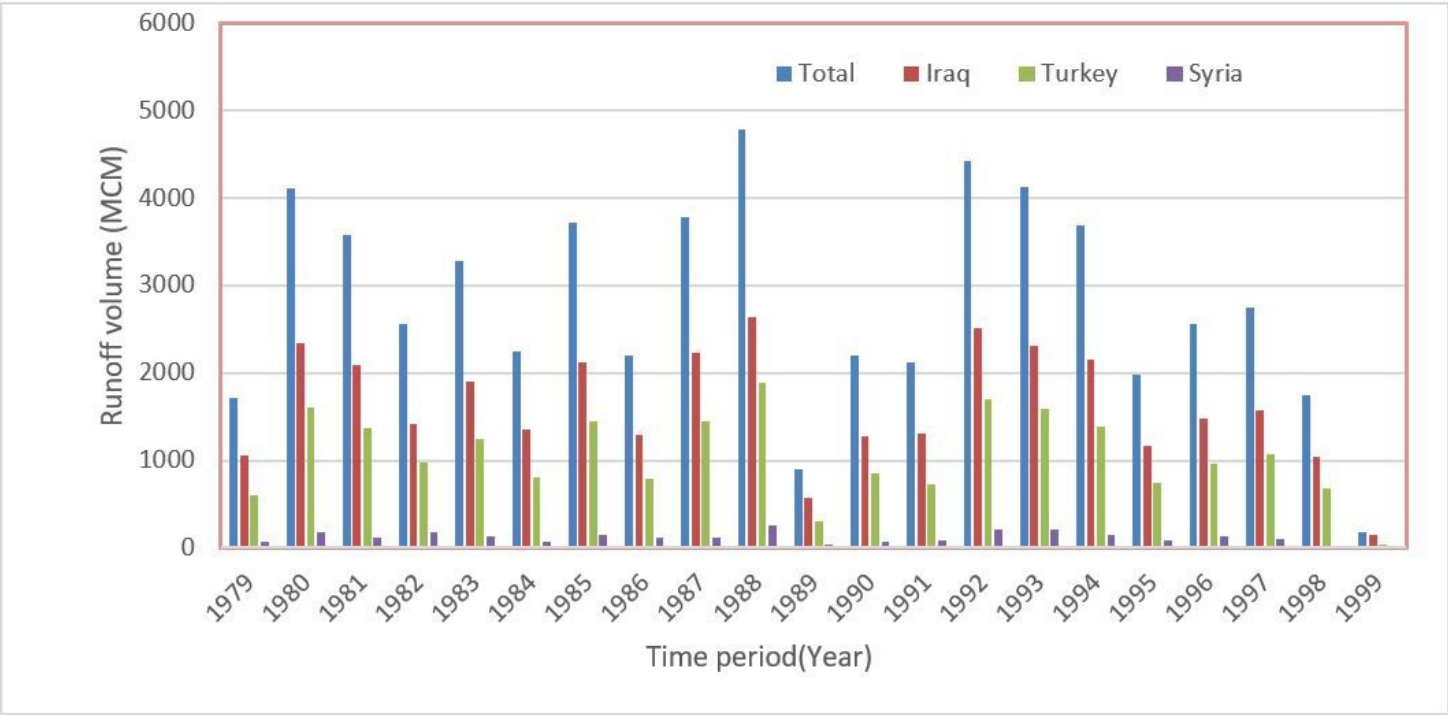

Figure 11

Annual runoff from sub – basins within the watershed for period (1979 -1999)