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Estimation of the Surface Runoff Volume of Al-Mohammedi Valley for Long-Term period using SWAT Model

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ABSTRACT

The management of water resources requires adequate information on the quantities of water supplied from the basins that outfall into a river, especially during the flood seasons. The study area located in the western part of Iraq within the administrative boundaries of the Heet district about 70 km from Haditha Dam, 45km from Ramadi in Anbar province. The study aims to evaluate the amount of surface runoff through a long-term period (1981-2019). Soil and Water Assessment Tool (SWAT) related to Geographic Information System (ArcGIS) was used for the simulation. The input data was the Digital Elevation Model (DEM) of SRTM with resolution 30m, land use/land cover map from the European Space Agency (ESA) with resolution 300m and, soil map from the Food and Agriculture Organization (FAO). The weather data used in the study were obtained from the Climate Forecast System Reanalysis (CFSR) combined with the weather data from the Surface meteorology and Solar Energy (SSE) produced by NASA. These weather data prepared using SWAT weather database software to be ready for the simulation processes. Al-Mohammedi valley was calibrated and validated using SWAT-CUP software using the available recorded discharges at Heet, Ramadi, and Al-Warar gauge stations. The calibration is based on the meteorological data for the period January 1, 2002, to December 31, 2006, and the validation was based on the data between January 1, 2007, to December 31, 2009. The model calibration and validation results based on two objective functions "Nash-Sutcliffe (NS) and coefficient of determination(R2)" showed that SWAT was successfully simulated Al-Mohammedi valley with NS = 0.72 and R^2 = 0.76 for calibration, and NS = 0.63 and R^2 = 0.65 for validation. According to SWAT results, the average runoff volume in the long-term period of simulation from January 1, 1981, to October 31, 2019, was 79.2 million m^3 while the average runoff depth was 18.25 mm with about 17 % of rainfall becomes surface runoff.

1. Introduction

Surface runoff generated by rainfall is significant in various activities in the hydrological studies of water resources engineering such as hydraulic structure design(eg. spillway), controlling floods hazards, and generation of electric power, etc.(Mishra et al., 2013).

Water resource management requires extensive information on the amount of surface water supplied by the river basin. the lack of hydrological data makes it difficult to predict the runoff events, this makes large amounts of surface runoff a risky to rainy plants and the population by soil erosion or floods. Climatic changes in arid and semi-arid regions that are represented by sudden and uneven rainfall and the diversity of terrain makes surface runoff happen randomly. Along with climate change, the heterogeneity of soil properties has also a significant effect on the runoff surface of different basin areas. Thus, In order to identify these differences in watersheds, the hydrologic cycle and other hydrological phenomena should be studied. At the present time, different hydrological models have been developed to check the climate change impact and soil characteristics on the hydrological cycle. The input data used by most of these models are maximum and minimum temperature, precipitation, topographical characteristics, soil properties, land cover, and other hydrological parameters. All these models can simulate very complex and large basins (Devia et al., 2015).

In rainfall-runoff models, the spatial processes provide a means to represent a model for a catchment. It depends on the model inputs and

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how the runoff surface is formed and directed through watersheds. Variation in surface parameters (eg. Topography, soil, and land cover) affects the linkage between rainfall and surface water in watersheds and must be taken into account in modeling (Beven, 2012). Rainfall-runoff models can be categorized based on the spatial structure of catchment processes into lumped, distributed, and semi-distributed models. Lumped models do not take into account spatial variations within watersheds while the spatial variations are treated in grid cells in distributed models. Some spatial variations are reflected in semi-distributed models but the runoff surface is not calculated for each grid cell as in distributed models (Sitterson et al., 2017).

The Soil and Water Assessment Tool (SWAT) is a semi-distributed model developed to predict the runoff surface, sediment concentration and water quality in ungauged catchments (Devia et al., 2015). SWAT software is integrated between the semi and fully-distributed models. It is effective in performing long-term simulations for these purposes SWAT was chosen in this study.

Several successful studies have conducted using SWAT software for the watershed simulation, have proven that SWAT is a good software for the runoff simulation (Al-khafaji and Saeed, 2018) (Vilaysane et al., 2015) (Alwan and Mohammed, 2016) (Hussein et al., 2016) (Ang and Oeurng, 2018).

For the purpose of checking the efficiency of the model during a period of long-term of simulation with the change of land use through time, (Al-Khafaji et al., 2017) performed a study to examine the SWAT performance for a long-term period (1986-2013) simulation with the land cover changes for Adhaim watershed north of Iraq. The study results show that SWAT can be useful in discovering the changes in the Landuse/Landcover for the simulations in the long-term.

The objectives of this study firstly to check the performance of SWAT in Simulating Al-Mohammedi basin, secondly to evaluate the amount of runoff volume with a long-term period (1981-2019).

1.1 Study Area Description

Al-Mohammedi basin located in the western part of Iraq within the administrative boundaries of the Heet district about 70 km from Haditha Dam, 45km from Ramadi in Anbar province Between latitude (32°46´22″ - 33° 38´37″) north and longitude (40°23´45″ - 42° 57´56″) east. It is bordered from the north by the Wadi al-Baghdadi, the north-west by Wadi Horan, the west by the valley of Amij and the south and south-west by Valley Ghadaf, where it flows into the Euphrates River from the West Bank. Temperature limits for the warmest month (August) is 42°C and in the coldest month (January) is 15°C *(CFSR,2015)*. The precipitation begins annually from October to May with an average rainfall depth of 104.6 mm, while relative humidity ranges from 13% in summer to 47% in winter *(CFSR,2015).*

2. Materials and Methods

2.1 *Soil & Water Assessment Tool (SWAT)*

SWAT (Soil & Water Assessment Tool) is a river, watershed, or basin scale-model deve loped for the USDA Agricultural Research Service (ARS) by Dr. Jeff Arnold (Neitsch et al., 2011). It is used to predict the effects of practices of land management on surface water, sediment, and agricultural chemical yields for a long time period within large ungauged watersheds (Neitsch et al., 2011). SWAT is a physically-based model which is required specific inputs details about the weather, soil properties, topography, vegetation, land cover changes that occurs in the watersheds (Neitsch et al., 2011). In the model processes, a watershed can be partitioned into a number of sub-basins, which divided into Hydrologic Response Units (HRUs) (Neitsch et al., 2011). The main model components including weather, hydrology, soil temperature, plant growth, nutrients, pesticides, and land management (P. W. Gassman et al., 2013).

The land phase of the hydrologic cycle is based on water balance equation (Neitsch et al., 2011):

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

Where, SW_t is soil water content (final state) (mm); SW_0 is soil water content (initial state) (mm); t is time (days); R_{day} is the precipitation amounts per day i (mm); Q_{surf} is the surface runoff amounts per day i (mm); E_a is the evapotranspiration amounts per day i (mm); w_{seep} is the percolation amounts and bypass flow that exiting the soil layers bottom per day i (mm); Q_{gw} is the return flow amount per day i (mm).

2.2 Input Data

This section deals with the input data used in the simulation of SWAT software for the long-term period including Digital Elevation Model (DEM), soil map, land use map and weather data and the observed discharge for the purpose of calibration and validation using SWAT-CUP software.

2.2.1 Digital Elevation Model (DEM)

The digital elevation models with 30m resolution downloaded from https://earthexplorer.usgs.gov/ for elevation ranges and spatial data of the study area depend on DEM provided by the global Shuttle Radar Terrain Mission (SRTM) from USGS, (fig. 1). These DEMs were merged and reprojected to the UTM zone to be ready for the Arc SWAT processes for delineation of the watersheds and flow directions.

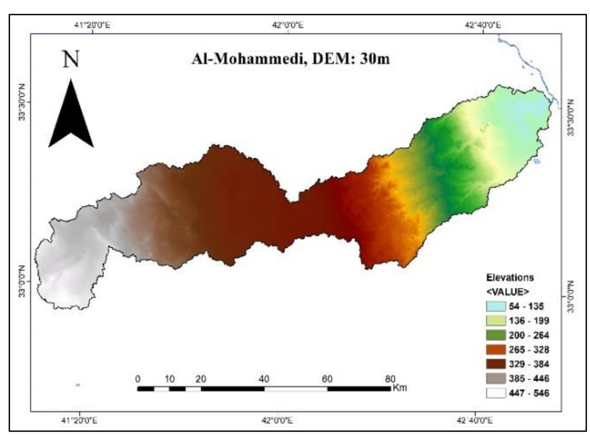

Fig. 1 Al-Mohammedi valley DEM with 30m resolution.

2.2.2 Land use Map

The global land cover map was used for the European Space Agency GlobCover Portal with resolution 300m for the period December 2004 - June 2006 (http://due.esrin.esa.int/page_globcover.php). The study area contains four land-use classes including Bare areas, Sparse vegetation, Shrub or Grassland, Croplands figure (2).

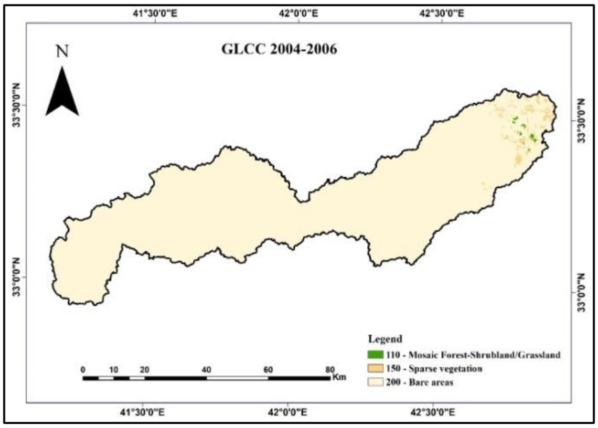

Fig. 2 Al-Mohammedi Land-use Map.

2.2.3 Soil Map

The soil Map used in the study was from the Food and Agriculture Organization(http://www.fao.org/geonetwork/srv/en/metadata.show?id=14116) at scale 1: 5000 000. The map divided into a number of polygons (fig.3). Each polygon contains different properties of study area soils such as hydrological soil group, hydraulic conductivity, soil texture, and other physical and chemical properties matched with the FAO soil database. These polygons were clipped to identify with the watershed area then reclassified for the definition of Hydrological Response Units (HRUs). Soil data are merged using ArcGIS processes with DEM, Land-use, and slope classes into SWAT in order to define the HRU level.

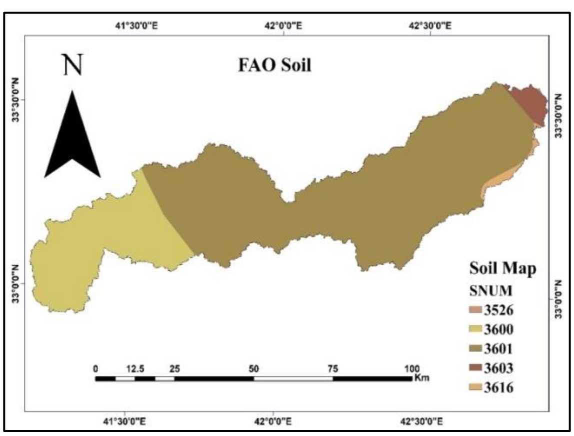

Fig. 3 Al-Mohammedi soil map. (FAO,1995)

Table 1 – Soil data classes of Al-Mohammedi basin with their percentage of the total watershed area.

Class	Value	Area %	Hydrologic Soil group
Yy12-a	3616	1.01	D
Yk34-b	3603	1.95	D
Yk32-a	3601	73.08	D
Jc38-2-3a	3526	0.02	D
Yk32-a	3600	23.95	D

2.2.4 Weather Data

SWAT requires climate data, including (precipitation, solar radiation, maximum and minimum temperature, relative humidity, wind speed) with the location of each weather station. Previous daily rainfall data were obtained from the Iraqi Metrological Organization and Seismology (IMOS) for Heet, Ramadi, and Haditha stations the period 2001 - 2017. It is stated that these data are invalid for use in the SWAT simulations. Weather data that needed to run SWAT should be continuous daily time-step, However, the weather data from IMOS is losing years and some months of weather data. Therefore, another source of weather data was used in the study called the Climate Forecast System Reanalysis (CFSR). A weather data for regions that missing weather stations, can be provided by CFSR. CFSR climate data are available for the period 1979-2014. A study by Fuka et al.,(2014) showed that the weather data produced CFSR to use for purpose of watershed simulations are good or better than weather data used in simulation produced by traditional weather stations. Since the CFSR data does not provide data for the recent years (2014-2019), other data source "The Surface meteorology and Solar Energy (SSE)" produced by NASA was employed for obtaining daily weather data for the period from January 1, 2014, to November 31, 2019. To supplement the climate data of the CFSR data, five weather stations cover the study area were selected using the 'POWER Single Point Data Access' option to get weather data for three valleys. Weather stations of two data sources are clarified in figures 4 and 5.

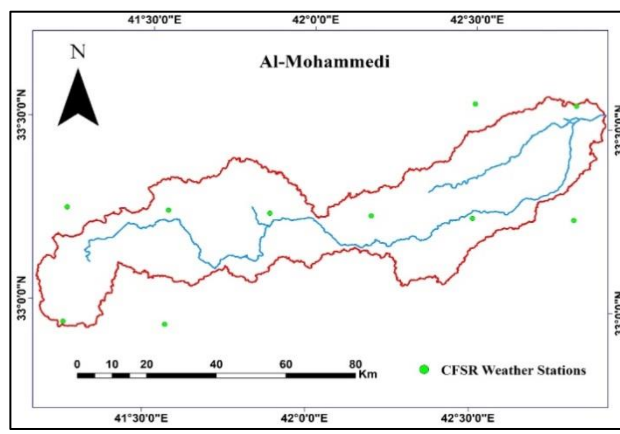

Fig. 4 Weather stations of the CFSR distribution in Al-Mohammedi valley

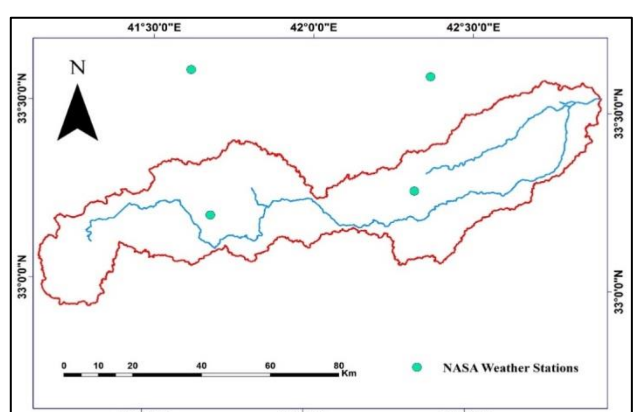

Fig. 5 Weather stations of NASA distribution in Al-Mohammedi valley.

2.2.5 Observed Discharges

Unfortunately, there were no gauging stations on the outlet of each valley. Therefore, the data collected were the daily flow discharge of the stations located on the Euphrates river flow line including Heet, Al- Warar regulator and Ramadi dam stations for the period (2002-2009) from the National Center for Water Resources Management/ Iraqi Ministry of Water Resources (MoWR). Al-Mohammedi valley outlet is located between Hit and Ramadi stations. Thus, the discharge data were used to find the average monthly discharges of Al-Mohammedi valley to be used in calibration and validation by using the water balance calculations that were used for rainy months only between Heet and Ramadi stations.

Two equations were used to compute Al-Mohammedi discharges based on two assumptions based on the flow discharges within the three gauge stations :

1. If the amount of discharge from Ramadi and Al-Warar stations is greater than the discharge passes from the Hit station, this indicates that there was an increase in the water passing from Heet to Ramadi and the following equation will be applied to compute the increase in water:

$$Q_{Mohammedi(in)} = Q_1 + (Q_3 + Q_2) - Q_{consumption(out)} + Q_{drainge(in)} \quad (2)$$

2. If the discharges from Ramadi and Al Warar stations are less than the water passing through the Heet station, this indicates that the increasing amount of water has been stored at the front of the dam, thus the following equation will be applied to calculate the amount of increase:

$$Q_{Mohammedi(in)} = Q_1 - (Q_3 + Q_2) - Q_{consumption(out)} + Q_{drainge(in)} \quad (3)$$

Where: Q_1 is the discharge at Heet gauge station (m^3/s), Q_2 is the discharge at Ramadi dam (m^3/s),Q_3 is the discharge at Al-Warar regulator (m^3/s), $Q_{consumption(out)}$ is the consumption discharges between Heet and Ramadi gauging stations (m^3/s), $Q_{drainge(in)}$ is drainage water between Heet and Ramadi gauging stations (m^3/s) as in (fig.6).

The results of the two equations are considered as the stream flow is charges of Al-Mohammedi valley. Using these results for the calibration of Al-Mohammedi basin runoff parameters.

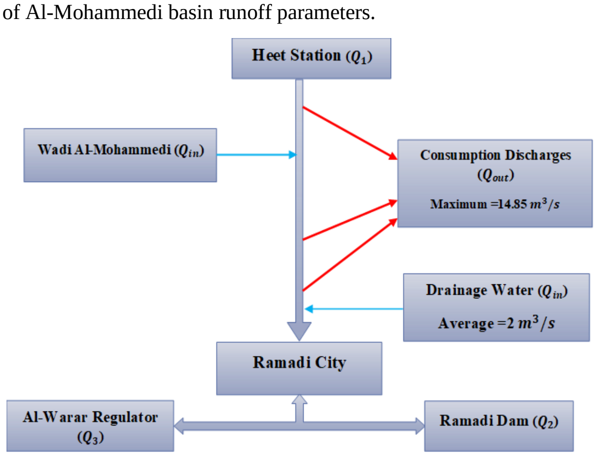

Fig. 6 A flowchart Show stream-flow gauging stations with the outlet of Al-Mohammedi Valley.

2.3 Implementation of the SWAT model

Arc SWAT version 2012 as an extension of ArcMap 10.4.1 related to the GIS software group was employed in this study for the determination of runoff surface amounts. The input data used for hydrological modeling are DEM with 30m resolution, land use/ land cover map. Al-Mohammedi watershed was divided into seven sub-watersheds with a total area of 4342.6 km^2 (as in figure 7). Thus, the model sub-divided the Al-Mohammedi watershed into 80 Hydrological response units (HRU) based on the changes in the classification of land use, soils, and slope. The prediction of runoff volume in the SWAT simulations is based on the water balance equation using the hydrological and weather data.

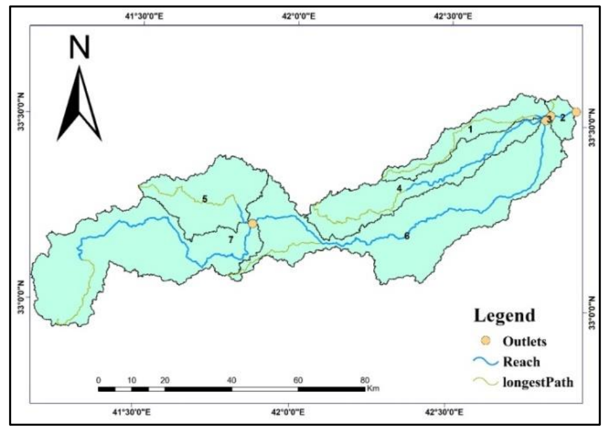

Fig. 7 Map showing watershed characteristics for Al-Mohammedi Valley.

2.4 Calibration and Uncertainty Analysis Using SWAT-CUP software

SWAT-CUP is a software developed for analyzing the uncertainties in the prediction of SWAT software outputs through calibration and validation periods (Abbaspour, 2015). Sequential Uncertainties Fitting Ver-2 (SUFI2) algorithm related to SWAT-CUP was used in the calibration.

The parameters uncertainty in SUFI-2 are explained as ranges (uniform distributions), which is calculated for all uncertainties sources like conceptual model parameters, driving variables (e.g., rainfall) and the measured data (Abbaspour, 2015). The uncertainties in the variables of the model outputs(which is expressed as the 95% probability distributions) are caused by the parameter uncertainties increase .

In SUFI-2, there are two static measures: R-factor and P-factor, which provided to determine the degree of suitability between simulation results and observation (Abbaspour, 2015). The P-factor is the percentage of measured data bracketed by 95% prediction uncertainty (95PPU). Another static measure is the R-factor, which is expressed as the 95PPU band's average thickness divided by the standard deviation of the measured data. The ranges of R-factor are between 0 and infinity and the P-factor values are between 100% and 0. For the perfect simulation in which the simulation results exactly match the measured data, the R-factor and P-factor should be zero and 1.

Two objective functions in SWAT-CUP were used to check the performance of the model in the simulation of the Al-Mohammedi basin. Nash-Sutcliffe (Nash and Sutcliffe, 1970) and the coefficient of determination are the most used objective functions in the calibration and validation processes.

1. The Nash-Sutcliffe coefficient is given by the equation:

$$NS = 1 - \frac{\sum_i (Q_m - Q_s)^2}{\sum_i \left(Q_{m,i} - \bar{Q}_m\right)^2} > 0.5 \quad (4)$$

Where NS is the Nash-Stucliffe coefficient, Q is discharge (or any variable), *s* is the discharge simulated, *m* is the discharge measured, and the bar stands for average.

2. The coefficient of determination is given by the equation:

$$R^2 = \frac{[\sum_i (Q_{m,i} - \bar{Q}_m)(Q_{s,i} - \bar{Q}_s)]^2}{\sum_i (Q_{m,i} - \bar{Q}_m)^2 \sum_i (Q_{s,i} - \bar{Q}_s)^2} > 0.6 \quad (5)$$

Where, R^2 is coefficient of determination, Q is discharge (or any variable), *s* is the discharge simulated, *m* is the discharge measured, and the bar stands for average, i is the i^{th} measured or simulated data.

2.5 SWAT Runs

After finalizing all input data, SWAT was run for three periods of the simulation using two years as a warm-up period. The first one was for the calibration from January 1st, 2002 to December 31st, 2007, the second was for validation from 1st, 2008 to December 31st, 2009 with monthly time-steps, and the last one was for a long-term period from 1st, 1981 to December 31st, 2013 with a yearly time-steps.

3. Results and Discussion

3.1 Sensitivity Analysis

Ten sensitive parameters were selected based on the most common parameters used in 64 selected watershed studies including CN2, ALPHA_BF, GW_DELAY, GWQMN, SOL_AWC, SOL_K, ESCO, EPCO, SURLAG, and OV_N (Arnold et al., 2012). The SWAT runoff parameters chosen for calibration were used in the sensitivity analysis on the monthly time steps of the observed discharges of the Al-Mohammedi basin using SWAT-CUP. The sensitivity analysis was executed using T-Statistics and P-value methods to evaluate the impact of these parameters on the SWAT runoff discharge in statistically. The t-stat and p-value results show that the Runoff curve number (CN2), Manning's "n" value for overland flow (OV_N), Available soil water capacity (SOL_AWC), and Soil evaporation compensation coefficient (ESCO) are the most sensitive parameters for Al-Mohammedi valley as in (table-2).

Table 2 – Sensitivity analysis of the runoff parameters.

Parameter Name (Parameter Description)	t-stat	p-value
r_CN2.mgt (Runoff curve number)	39.278	0.000
v_ALPHA_BF.gw (Alpha baseflow factor)	1.238	0.216
v_GW_DELAY.gw (Groundwater delay time)	-1.149	0.251
v_GWQMN.gw (Treshold water depth in the shallow aquifer required for return flow to occur)	-1.880	0.061
v_ESCO.hru (Soil evaporation compensation coefficient)	7.456	0.000
v_EPCO.hru (Plant uptake compensation coefficient)	0.607	0.544
r_SOL_AWC().sol (Soil available water capacity)	-19.537	0.000
v_OV_N.hru (Manning's "n" value for overland flow)	-4.706	0.000
v_SURLAG.bsn (Surface runoff lag coefficient)	-1.226	0.221
r_SOL_K().sol (Saturated hydraulic conductivity)	0.022	0.983

3.2 Calibration and Validation Results

SWAT was run for-Mohammedi basin the period from 2000 to 2009 with disregarding the first two years since the model required a warm-up period. It is necessary to add a warm-up period for purposes of model parameters stabilization (e.g. groundwater depth) since the results may change significantly from the observed data. Thus, the final model periods for calibration and validation were from 1, January 2002, to 31, December 2009. All sensitive parameters are taken into consideration in the SWAT calibration. The model was calibrated at the outlet of reach 2, sub-basin 2 where the water outfall into the Euphrates river. The calibration and parameter correction process is necessary in order to make SWAT produce results that are closer to that observed discharges.

Table (3) shows the results of p-factor, r-factor, R^2, and NS values for the time series. From table 3, it can be concluded that the model results are very good from the NS coefficient of 0.76 and R^2 of 0.72. Figure (8) shows the obtained graphs of calibrated and validated periods.

Table 3 – Criteria for testing the accuracy of the model calibration and validation for Al-Mohammedi valley.

Model Evaluation	R^2	NS	P-factor	R-factor
CALIBRATION (2002 - 2006)	0.76	0.72	0.62	0.19
VALIDATION (2007 – 2009)	0.65	0.63	0.11	0.34

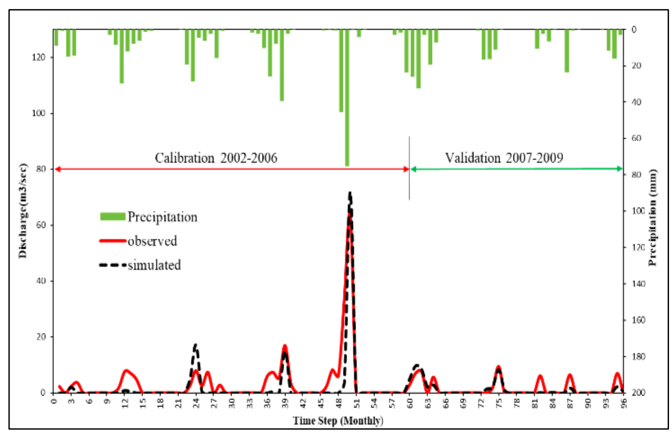

Fig. 8 Comparison between the simulated and observed discharges in monthly time step for both calibration and validation period.

3.3 Surface Runoff Volume Prediction

After the calibration of Al-Mohammedi Valley, the SWAT software operated for the period of long-term (1981-2019) to find the amount of surface runoff volume. In 40 years of simulation (1981-2019), the average curve number for the Al-Mohammedi basin was 75.76 and the annual precipitation was 103.4mm. The average value of the surface runoff depth was 18.25 mm with about 17 % of rainfall becomes surface runoff and the average annual ET result 73 mm. Furthermore, SCS-CN is the main method that SWAT computes the runoff quantities for a basin. The results of this method inserted into the water balance equation to reduce losses such as evaporation and the amounts of water that seep into the soil to calculate the net runoff. The average runoff volume for the Al-Mohammedi basin was 79.27 Mm3 (18.25 mm) over the period from January 1, 1981, to November 31, 2019 (fig.9). Furthermore, The maximum daily flow discharges for the long-term period (1981to 2019) for Al-Mohammedi valleys are 160 m^3/s and the maximum flow discharges per one square kilometer unit are 0.037.

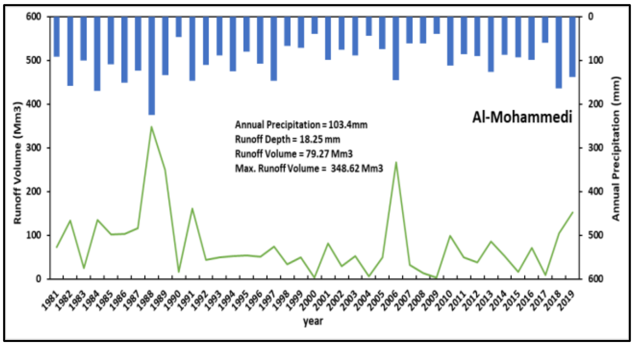

Fig. 9 Graph shows runoff amounts of Al-Mohammedi valley during the long-term period of simulation (1981-2019).

4. Conclusions

In this study, Arc SWAT software was examined and used in the long-term simulation for the Al-Mohammedi basin. From the results, it can be noticed the following conclusions:

1. The results of the objective functions selected in calibration and validation using SWAT-CUP software show that SWAT was successfully simulated Al-Mohammedi valley for a period from January 1, 2002, to December 31, 2006, using average monthly discharges with NS = 0.72 and R^2 = 0.76 for calibration, and NS= 0.63 and R^2=0.65 for validation.
2. The most sensitive parameters in SWAT software are the runoff curve number (CN2), soil evaporation compensation coefficient (ESCO), available soil water capacity (SOL_AWC), and Manning's "n" value for overland flow (OV_N), according to the calibration results for Al-Mohammedi valley, and the average curve number for Al-Mohammedi valley was (75.8).
3. In 40 years of simulation (1981-2019), the annual precipitation was 103.4mm and the average value of the surface runoff depth was 18.25 mm with about 17 % of rainfall becomes surface runoff and the average annual ET result 73 mm.
4. The maximum daily flow discharges for the long-term period (1981to 2019) for Al-Mohammedi valleys are 160 m^3/s and the maximum flow discharges per one square kilometer unit are 0.037.

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