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Modelling streamflow using SWAT model: a case study of Thuthapuzha river basin, Kerala

FOUSIYA and ANU VARUGHESE

Department of Irrigation and Drainage Engineering
KCAET, Tavanur, Malappuram 679573 Kerala, India
Email for correspondence: fousy10071995@gmail.com

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ABSTRACT

Land, water and vegetation are the three basic resources that support life on earth with water being the most widely distributed natural resource. The best way to address water related issues is to manage water resources in a single river basin system. Hydrological models are considered to be an important tool in the management of water resources. The Soil and Water Assessment Tool (SWAT) model was used to model streamflow in the Thuthapuzha watershed in Kerala. The simulation period for calibration was 1989 to 2009; for validation of the model, data from 2010 to 2017 were used and the simulation was done on daily basis. The initial period of three years (1989-1991) was taken as a warm-up period. Two indices viz p-factor and r-factor were considered in the SWAT-CUP uncertainty analysis. During calibration the p-factor and the r-factor were 0.77 and 0.64 and during validation the p-factor and the r-factor were 0.85 and 0.56 respectively. The performance of the model was assessed by Nash-Sutcliffe Efficiency (NSE), coefficient of determination (R^2), and per cent bias (PBIAS). The R^2, NSE and PBIAS values were 0.88, 0.88 and -1.4 for the calibration period and 0.8, 0.8 and 5.4 for the validation period respectively. Overall model statistics have shown that streamflow simulation could be successfully performed in the Thuthapuzha watershed using the developed model.

Keywords: SWAT; NSE; PBIAS; SWAT-CUP; calibration; validation; sensitivity analysis

INTRODUCTION

Water is the most widely dispersed natural resource and is constantly challenging to its demand every day. Freshwater supplies face intense competition and their availability in many parts of the world is limited. Presently 47 per cent of the world's population lives in areas suffering from water shortages for at least one month per year. Most countries in the world are facing lack of water availability compared to their increasing demand. It is clear from the ever increasing population and security needs that both land and water resources need to be managed and used in an effective and comprehensive manner. Hydrological models are becoming vitally important for current and future water resource management. According to Chow et al (1988) the models represent the hydrological cycle as a system with different components such as inputs (precipitation) and outputs (runoff) linking these components using a set of equations. Watershed models capable of representing such processes can be used to improve knowledge of the relationship between hydrological processes, erosion and management practices. There are numerous models that can predict runoff, nutrient loss, sediment yield, erosion etc from a catchment such as SWAT (Soil and Water Assessment Tool) (Arnold et al 1998), EPIC (Erosion Productivity Impact Calculator) (Williams et al 1984), CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems) (Knisel 1980) etc. Numerous researchers have successfully used the SWAT model to predict flow and sediment yield (Pisinaras et al 2010, Nasrin et al 2013). The modelling of the hydrological balance of the watershed is the basis for almost all SWAT applications (Gassman et al 2007). Arnold confirmed the applicability of the SWAT model to simulate runoff at national, basin and small scales (Zhao et al 2013).

Although the Kerala state of India has an average rainfall of 3,000 mm per year, the state is experiencing serious water shortages during the summer season. Throughout the monsoon all the rivers flow full and many of them gradually dry up in summer. The second longest river in Kerala is Bharathapuzha, also known as the Nila, with a length of 209 km. The four main tributaries of the river are Kalpathipuzha, Gayatripuzha, Thuthapuzha and Chitturpuzha. The average annual discharge of Bharathapuzha is 3.94 km^3 of which approximately 42 per cent (1.6 km^3) is contributed by Thuthapuzha (Nikhil Raj and Azeez 2009). The river used to flow smoothly even in severe summer until a few decades ago. Significant climate change has also altered river flow patterns. Extreme climate change events can be adapted in the future through proper management of water resources. A modelling technique using SWAT was used for this work to simulate streamflow of Thuthapuzha watershed.

METHODOLOGY

Study area

Thuthapuzha, a sixth-order sub-basin covers an area of 905 km^2. It lies between latitude 10°50'N to 11°15'N and longitude 76°05' to 76°40' E. Of the total area, 75 per cent is in the Palakkad district and 25 per cent is in the Malappuram district. Thuthapuzha is approximately 63 km long and has four tributaries including Nellipuzha, Kanjirapuzha, Karimbuzha and Kunthipuzha (Warrier and Manjula 2014). It is the main tributary that supplies water to Bharathapuzha particularly during the summer months. The annual average discharge of Thuthapuzha sub-basin is 1,750 MCM. There are no other major structures in the watershed other than the reservoir constructed across Kanjirapuzha which serves as a source of irrigation water. The study area elevation varies from 20 meters amsl in the western side of the basin to 2,308 meters amsl in the northern side of the Silent Valley Reserve Forest. The average precipitation of the Thuthapuzha basin is 3,830 mm (Manjula and Warrier 2019) and the average temperature is 27.3°C (Tejaswini and Sathian 2018). Severe water scarcity and drought conditions have also been reported in the river basin in recent years. The location map of the study area is given in Fig 1.

SWAT (Soil and Water Assessment Tool)

SWAT is a spatially-distributed, physically-based watershed model capable of simulating the impact of land, topography and vegetation on water movements on and near the soil surface (Arnold et al 2012). SWAT is free software and is coupled to the GIS platform via ArcSWAT interface. In order to simulate flow and direct sub-basin routing, SWAT requires information on soil, land use and elevation. SWAT2012 (latest version) (Neitsch et al 2011) was used for this research and the ArcSWAT 2012 extension of GIS was used as an interface for SWAT modelling.

Main components of SWAT are weather, hydrology, soil properties, plant growth, nutrients, pesticides, bacteria and land management (Arnold et al 2012). The watershed is divided into different sub-watersheds depending upon the topography. Each sub-watershed has been further subdivided into Hydrological Response Units (HRUs) which are combinations of homogeneous land use, soil and slope (Arnold et al 2012). Many inputs such as DEM, soil type, land use and slope have an effect on the size of the HRU. Hydrology in the SWAT model can be divided into two main components including the land phase and the routing phase (Neitsch et al 2011). The land phase controls the amount of water, sediment and nutrient loads in each sub-basin to the main channel. The routing phase describes the flow of water, sediment etc to the outlet through the watershed channel network (Neitsch et al 2011). Based on the equation, water balance SWAT calculates the land phase hydrological cycle (Neitsch et al 2011) as follows:

$$\Delta SW = P - (QSURF + ET + WSEEP + QGW) \qquad \text{....(1)}$$

where ΔSW: Change in soil water content, P: Precipitation, QSURF: Surface runoff out of the watershed, ET: Evapo-transpiration, WSEEP: Percolation from the soil profile, QGW: Transmission losses from the streams

Input data for SWAT model setup

Digital Elevation Model (DEM), land use map, soil map, weather and discharge data are the primary datasets required for the SWAT model. These data were collected from different sources and some were prepared. Details on the sources of all datasets used in this study are shown in Table 1. The DEM for the study area is shown in Fig 2. Slope classification depends on the DEM. Land use map and soil map are shown in Fig 3 and Fig 4 respectively.

SWAT model setup

Once the ArcSWAT programme was downloaded, a toolbar was added to ArcGIS to develop the SWAT model showing the main procedures for the modelling process. Model setup

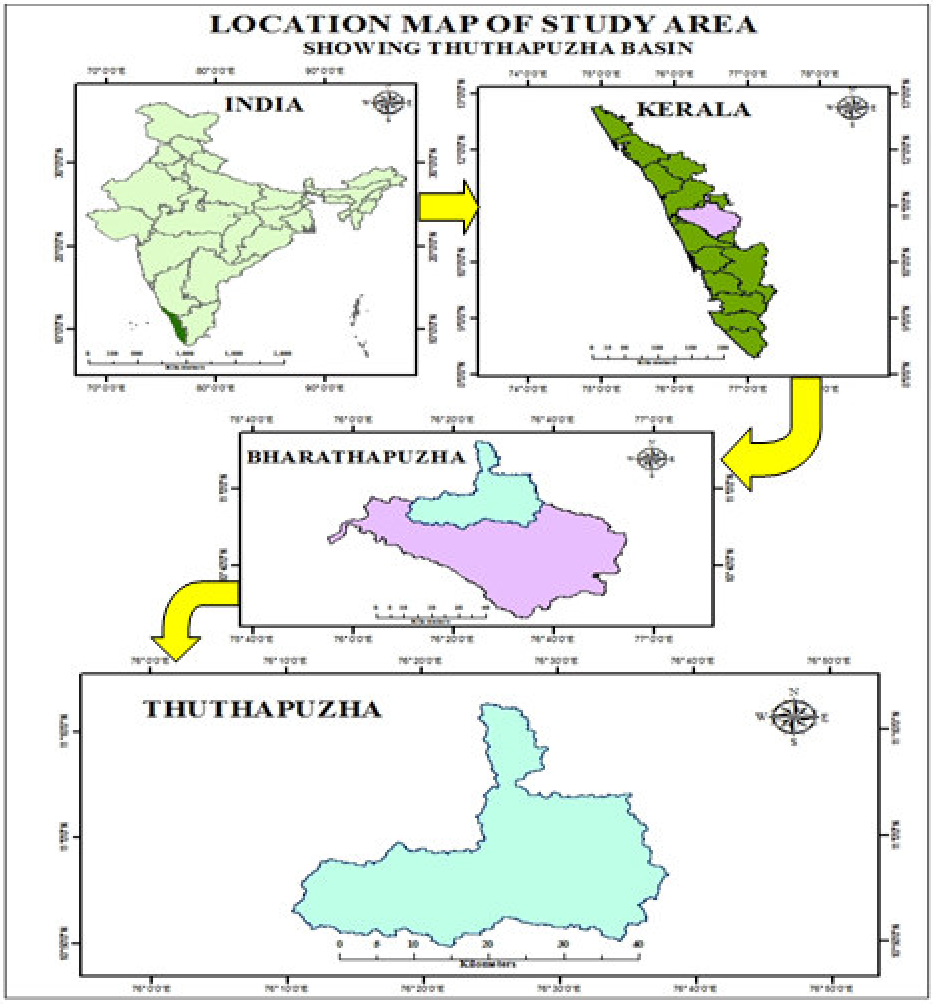

Fig 1. Location map of study area

Table 1. Input data of SWAT model

Data	Source		Data preparation
DEM	NASA SRTM Version 3.0 Global 1 arc second (SRTMGL1) from EARTHDATA website		DEM in 30 m resolution clipped for the study area and projected to WGS_1984_ UTM _Zone_ 43N
Land use	Landsat 4-5 TM, 2008 image downloaded from the USGS Earth Explorer		Supervised classification carried out using ERDAS IMAGINE 2014
Soil map	Collected from the Soil Survey and Soil Conservation Directorate, Kerala state		Soil map digitized and converted into the raster format in ArcGIS 10.4
Meteorology (1989-2017)	Precipitation	Regional Agricultural Research Station, Pattambi, Kerala and India Meteorological Department (IMD), Mannarkkad, Kerala	Location details and corresponding meteorological data prepared in text format for each parameter separately; sunshine hours converted to solar radiation as SWAT requires solar radiation in MJ/m²/day
	Minimum and maximum temperature	Regional Agricultural Research Station, Pattambi, Kerala and Central Water Commission (CWC), Pulamanthole, Kerala	
	Relative humidity, wind speed and sunshine hours	Regional Agricultural Research Station, Pattambi, Kerala	
River discharge	Central Water Commission (CWC) at the outlet of the Pulamanthole gauging site (1989-2017)		Calibration and validation of the SWAT model performed using the discharge data from CWC

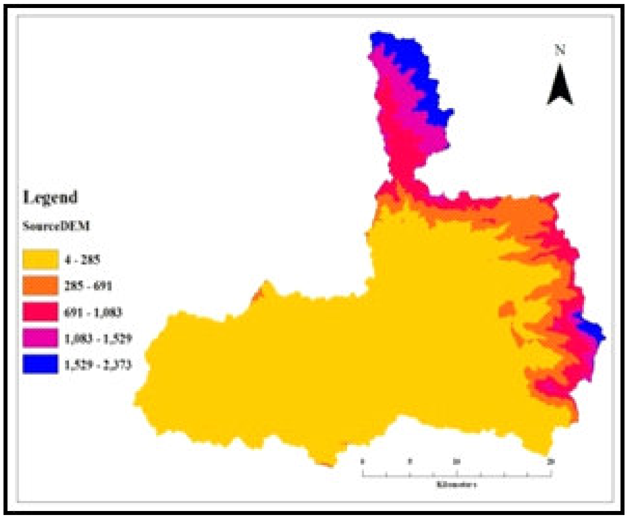

Fig 2. Digital elevation model of Thuthapuzha watershed

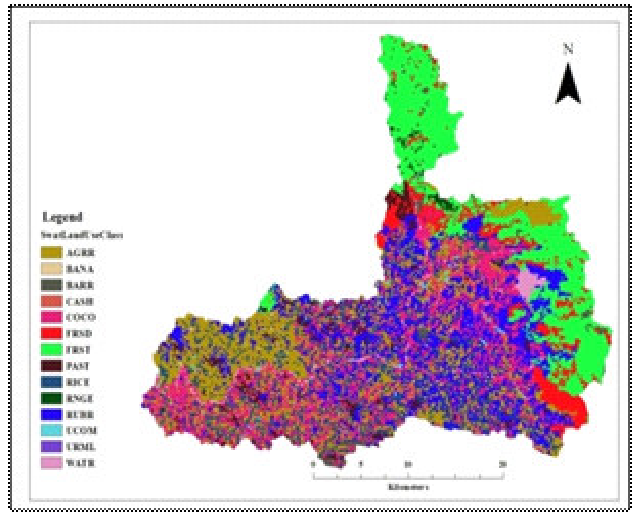

Fig 3. Land use map of Thuthapuzha watershed

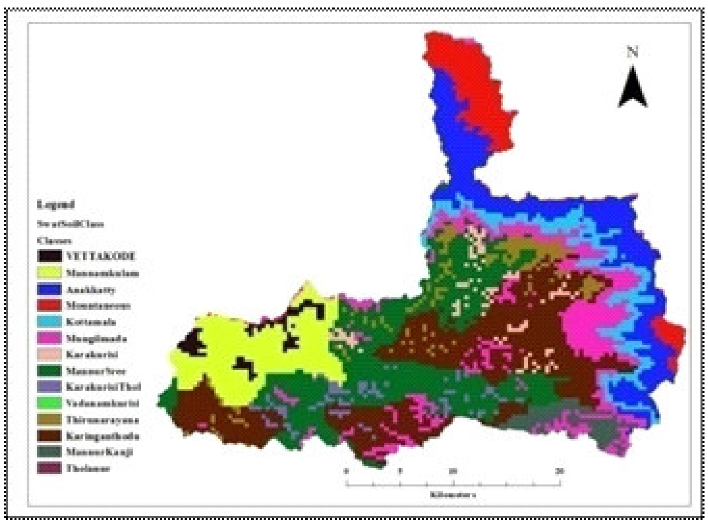

Fig 4. Soil map of Thuthapuzha watershed

includes watershed delineation, HRU analysis, writing input tables and SWAT simulation. DEM data were used in ArcSWAT to delineate the watershed boundary. Land use, soil and slope data were then overlapped to generate Hydrological Response Units (HRUs). The climate data including precipitation, temperature (minimum and maximum), wind speed, solar radiation and relative humidity from the available weather stations were then provided to the SWAT model. After importing all the required data, the initial watershed input values must be defined by using the write input table option. Using the information given to the model, the SWAT generated default input values for each HRU and sub-basin in the ArcGIS Geodatabase. All the spatial data used in ArcSWAT have been projected to WGS_1984_UTM_Zone_43N.

SWAT-CUP

SWAT-CUP (Calibration and Uncertainty Programmes) is an automated calibration tool for SWAT model developed by Eawag, a Switzerland-based aquatic research institute (Abbaspour 2015). The SWAT-CUP is a public domain programme using a generic interface. Within the SWAT-CUP, it is possible to perform different sensitivity analysis, calibration, validation and uncertainty analysis. The SWAT-CUP uses five different uncertainty algorithms (SUFI-2, PSO, MCMC, ParaSol and GLUE) (Abbaspour 2015). The SWAT-CUP systematically modifies uncertain model parameters; the model is run. The required outputs are then extracted from the model output files and compared with the data observed. For this study version 5.2.1 of SWAT-CUP 2019 was used.

SUFI-2 (Sequential Uncertainty Fitting) was chosen for the calibration of the SWAT model for this project. SUFI-2 is a semi-automatic programme in which the user manually performs some of the steps during the calibration process. SUFI-2 uses Latin hypercube sampling to generate a separate set of parameters (Abbaspour et al 2007). The uncertainty of the parameter is described in a multivariate uniform distribution in a hypercube parameter. When all types of uncertainty are included in the observed variables (eg discharge), the 95PPU (95% prediction uncertainty) generated by the uncertainty parameter defines all uncertainties.

Sensitivity analysis and calibration

The first step in the process of calibration and validation is the sensitivity analysis. Sensitivity analysis can be described as the process of determining the rate of change in the parameters of the model output relative to changes in the parameters of the model input. Two forms of sensitivity analysis are available; one-at-a-time and global analysis. This research conducted an analysis of global sensitivity using the SUFI-2 algorithm. A sensitivity measure was given by the t-stat value while the p-value calculated the significance of the sensitivity. SUFI-2 evaluates to what degree uncertainties are compensated for and provides a range of outputs. The SUFI-2 algorithm used 500 simulations with a 3 year warm-up period from 1989 to 2009 using 13 parameters. Each parameter was adjusted after iteration based on the ranges of parameters indicated by SUFI-2. Model calibration is essential to demonstrate that the model can produce the same results as the observed values. For SWAT model calibration, a total of three model iterations were used. The accuracy of the calibration was assessed on the basis of the proximity of the p-factor to 100 per cent and the prediction uncertainty on the basis of the proximity of the r-factor to 1. After calibration in the SWAT-CUP the parameters needed to be changed in the SWAT model were adjusted and the calibrated model was run.

Model validation

Once the model was calibrated, model validation was performed via the SWAT-CUP interface. Model validation was carried out by running the model with calibrated parameters without any further modification and comparing the new simulated daily discharge with the observed daily discharge. The SWAT model was run from 2010 to 2017 without any further adjustment of the calibrated parameters. The p-factor and r-factor were used to measure the uncertainty of the prediction and NSE, R^2 and PBIAS were used to evaluate the performance of the model.

Model performance

Nash-Sutcliffe Efficiency (NSE) is a commonly used statistical measure for hydrological modelling that is used as a measure of goodness of fit. Generally R^2 and NSE are measured together when evaluating the hydrological model performance (Zhou et al 2012). In addition to NSE and R^2 efficiency per cent bias (PBIAS) was also used in this research to evaluate model performance.

RESULTS and DISCUSSION

SWAT model setup

DEM data were used to delineate the watershed boundary corresponding to the outlet at the Pulamanthole gauging station in the SWAT model. Output selection helps to compare model results and observation data. For improved hydrographic segmentation and sub-basin delineation, drainage lines were provided in the model (Neitsch et al 2005). As a result the Thuthapuzha watershed was divided into 35 sub-basins. The study area contains 14 classes for land use. Agricultural row crops are the most dominant type of land use covering 20.30 per cent of the watershed area. The rubber and forests are the other dominant classes of land use in the study area. Karinganthodu and Mannursree are the main soil series contributing approximately 21.79 and 20.02 per cent respectively. Slope from the DEM was computed and reclassified the study area into four classes. Soil, land use and slope data were then overlapped to create HRUs. The soil, land use and slope threshold levels were identified below which unique areas of land use, soil and slope were not considered in sub-basins (Winchell et al 2013). Using SWAT threshold values helps in minimising the number of HRUs and enhances the SWAT model as well as the demand for computing (Winchell et al 2013). A total of 841 HRUs were thus created with 10 per cent threshold values for the three classes (land use, soil and slope). The simulation period was fixed between 1989 and 2009 (21 years) for calibration and 2010-2017 (8 years) for validation; the warm-up period was three years.

Sensitivity analysis and calibration using SWAT-CUP

Model was run 500 times (with the use of the parallel processing option in SWAT-CUP, great time savings can be made). Following iteration global sensitivity analysis tool (t-stat and p-value) was used to determine the most sensitive parameters. When iteration is completed, post-processing options are determined where 95 per cent prediction uncertainty and objective function are determined for all observed variables; a new set of parameter ranges is given. Iteration with the new suggested range of parameter sets was performed again. The procedure was continued until satisfactory results of the NSE, R^2 and PBIAS were achieved. Out of the thirteen parameters, eight of the most sensitive parameters were selected for calibration. Parameters ranking after sensitivity analysis including t-stat and p-value and fitted range of values are shown in Table 2. During calibration process, the model input values were adjusted to match the observed and simulated discharge. The calibration period was set at 21 years between 1989 and 2009. The dotty plot of the most sensitive parameter in SWAT-CUP shows the objective function values as a function of parameters. It also shows whether the objective function is sensitive to the parameter or not. When points are haphazard and scattered, it indicates that the sensitivity is small and the sensitivity is higher when there is a trend.

Model performance evaluation

Model performance was evaluated on the basis of three statistical parameters namely NSE (Nash-Sutcliffe Efficiency), R^2 (coefficient of determination) and PBIAS (per cent bias). As per the performance rating of the statistical measurements used, the performance of the model was analyzed for both the calibration and the validation period using discharge as a parameter. It was concluded from the values that the model was performing well during both periods. The general performance rating and model evaluation statistics for the monthly discharge of the Pulamanthole gauging station are shown in Table 3. Performance assessment based on scattered plot and time series graph for both calibration and validation is shown in Figs 5 to 8.

Table 2. Parameters ranking after sensitivity analysis and fitted range of values

Rank	Parameter	SWAT-CUP initial range	Range after calibration	p-value	t-stat
1	r__CN2.mgt	-0.2 to 0.2	-0.16 to0.08	-2.20	0.03
2	v__ALPHA_BF.gw	0 to 1	-0.43 to 0.52	-2.03	0.04
3	v__GW_DELAY.gw	30 to 450	-117.67 to 260.83	-2.04	0.04
4	v__GWQMN.gw	0 to 2	0.78 to 2.35	-0.86	0.39
5	r__SOL_AWC().sol	-0.2 to 0.4	0.09 to 0.66	3.34	0.00
6	v__ESCO.hru	0.8 to 1	0.90 to 1.10	0.99	0.32
7	v__CH_K2.rte	5 to 130	57.80 to 163.45	3.75	0.00
8	r__SOL_K().sol	0 to 100	30.04 to 90.16	-4.29	0.00
9	r__SOL_BD().sol	0.9 to 3	1.64 to 3.13	-0.11	0.91
10	v__CH_N2.rte	-0.01 to 0.3	-0.13 to 0.16	-0.53	0.59
11	a__SURLAG.bsn	0.05 to 24	11.53 to 34.50	-1.09	0.28
12	v__GW_REVAP.gw	0.02 to 0.2	0.10 to 0.26	1.06	0.29
13	r__EPCO.hru	0 to 1	0.14 to 0.71	-0.32	0.75

Table 3. General performance rating and model performance evaluation

Component	Performance rating		
	R^2	NSE	PBIAS
Performance			
Very good	R^2 >0.85	0.75 <NSE <1.0	PBIAS <±10
Good	0.75 <R^2 <0.85	0.65 <NSE <0.75	±10 <PBIAS <±15
Satisfactory	0.6 <R^2 <0.75	0.50 <NSE <0.65	±15 <PBIAS <±25
Unsatisfactory	R^2 <0.60	NSE <0.50	PBIAS >±25
Model performance			
Calibration period	0.88	0.88	-1.4
Validation period	0.8	0.8	5.4

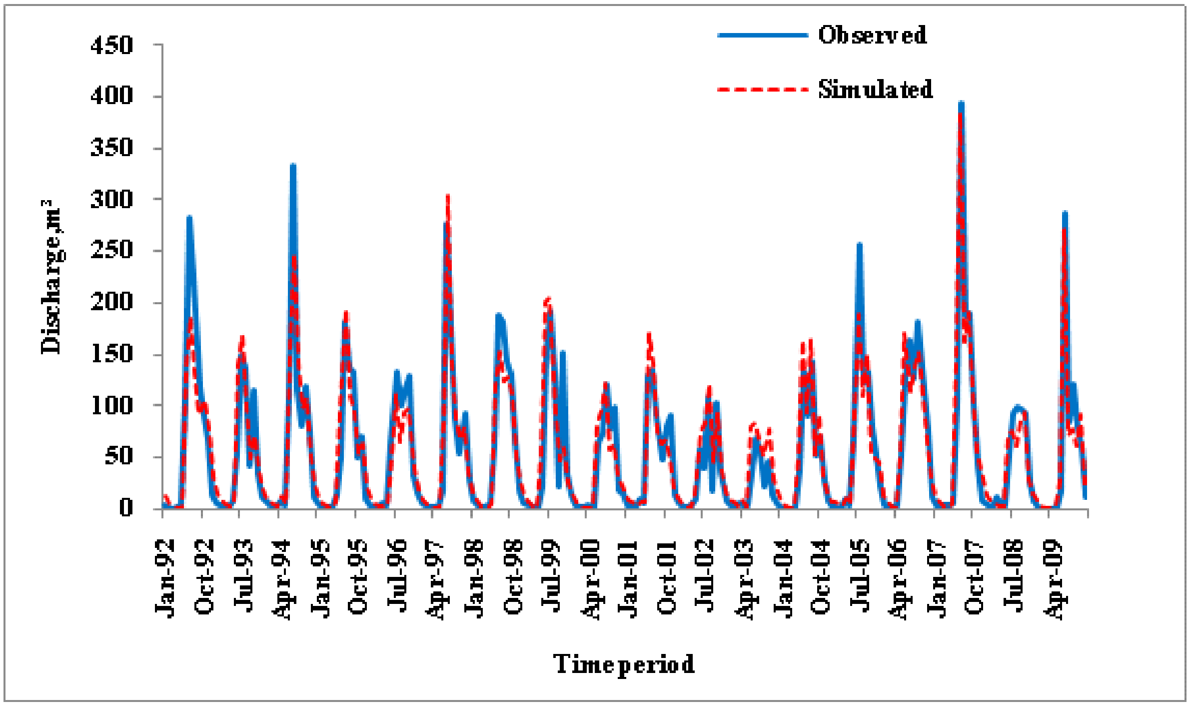

Fig 5. Observed and simulated discharge at Pulamanthole for calibration period

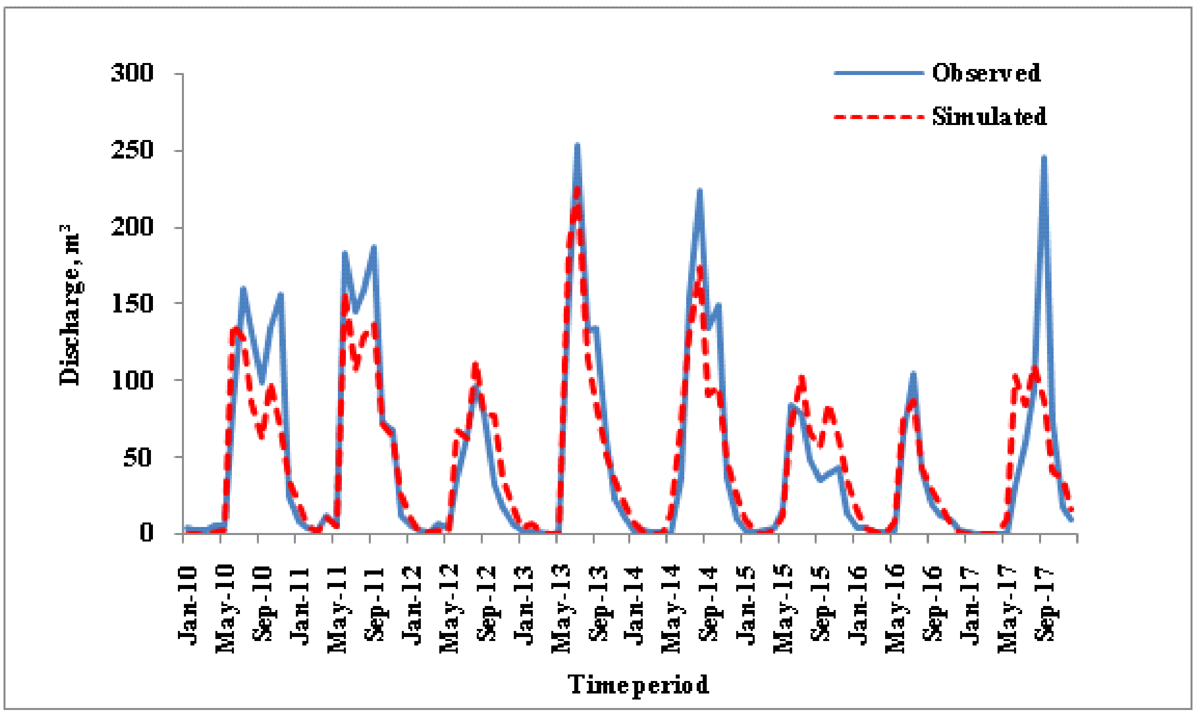

Fig 6. Observed and simulated discharge at Pulamanthole for validation period

Model validation

Following satisfactory calibration of the hydrological model (with very good performance statistics) the validation process was carried out. The validation period consisted of the remaining eight years (2010-2017). After calibration of the model, the validation of the model was performed using the SWAT-CUP interface. The SWAT model was run with eight calibrated parameters from 2010 to 2017 without any further parameter changes. The p-factor and r-factor were used to measure the uncertainty of the prediction and NSE, R^2 and PBIAS were used to evaluate the

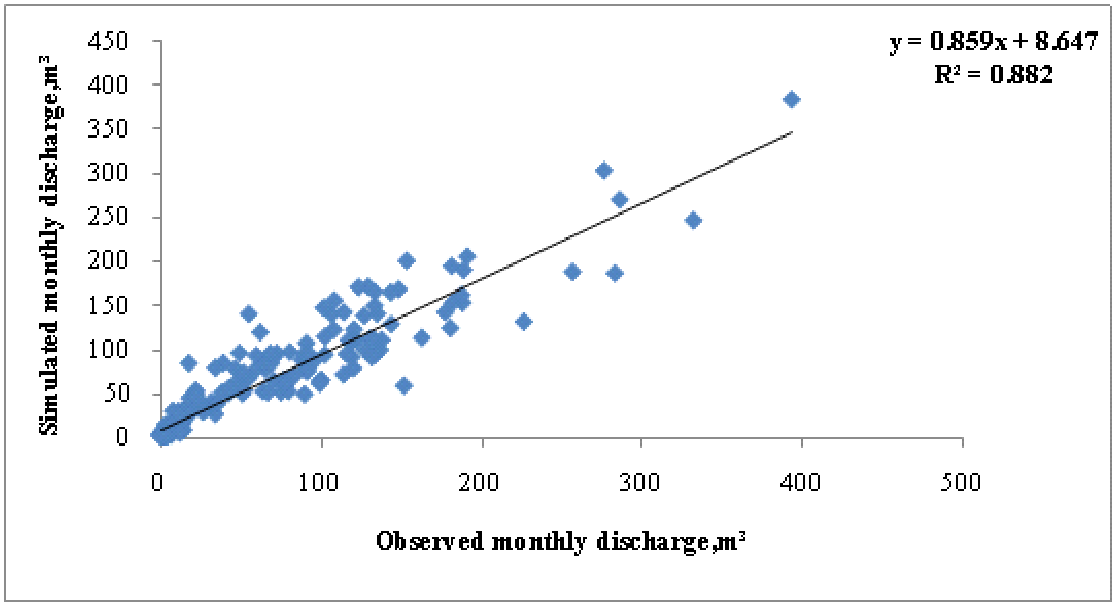

Fig 7. Scatter plot of observed and simulated monthly discharges at Pulamanthole gauging station during calibration period

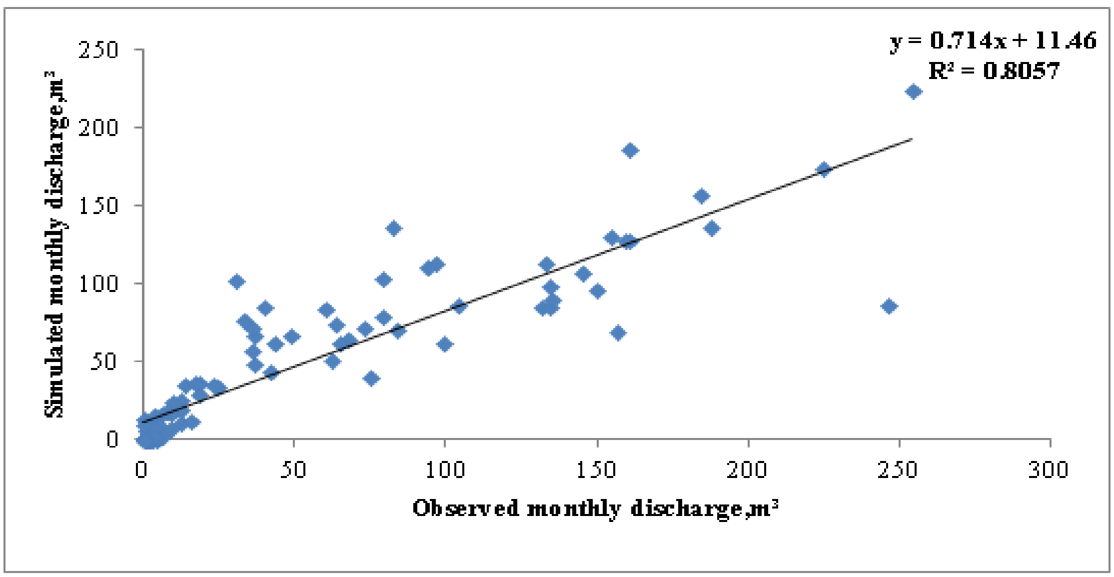

Fig 8. Scatter plot of observed and simulated monthly discharges at Pulamanthole gauging station during validation period

performance of the model. In calibration the p-factor and the r-factor were obtained as 0.77 and 0.64 and during validation, the p-factor and the r-factor were obtained as 0.85 and 0.56 respectively. The performance statistics also showed satisfactory results during validation. Overall model statistics has shown that streamflow simulation can be successfully performed in the Thuthapuzha watershed using the developed model. The 95 PPU plot obtained from SWAT-CUP and the corresponding rainfall distribution for the calibration and the validation period are shown in Fig 9. Streamflow simulated by the developed model for calibration and validation period was compared with the observed and found to be satisfactory (Fig 10).

CONCLUSION

For making a model suitable for a region, calibration and validation of the model need to be done. A well calibrated and validated model will be able to reproduce or predict different hydrologic variables for the future scenarios. Calibration

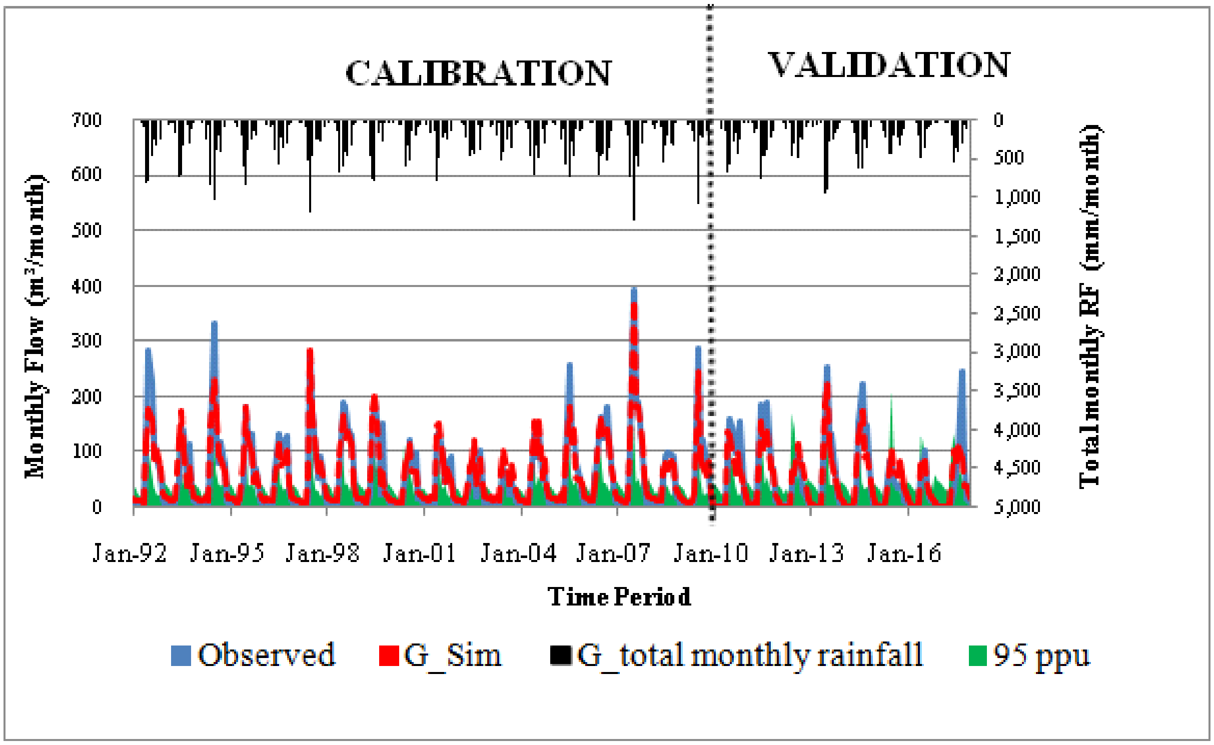

Fig 9. 95 PPU plot obtained from SWAT-CUP and corresponding monthly rainfall

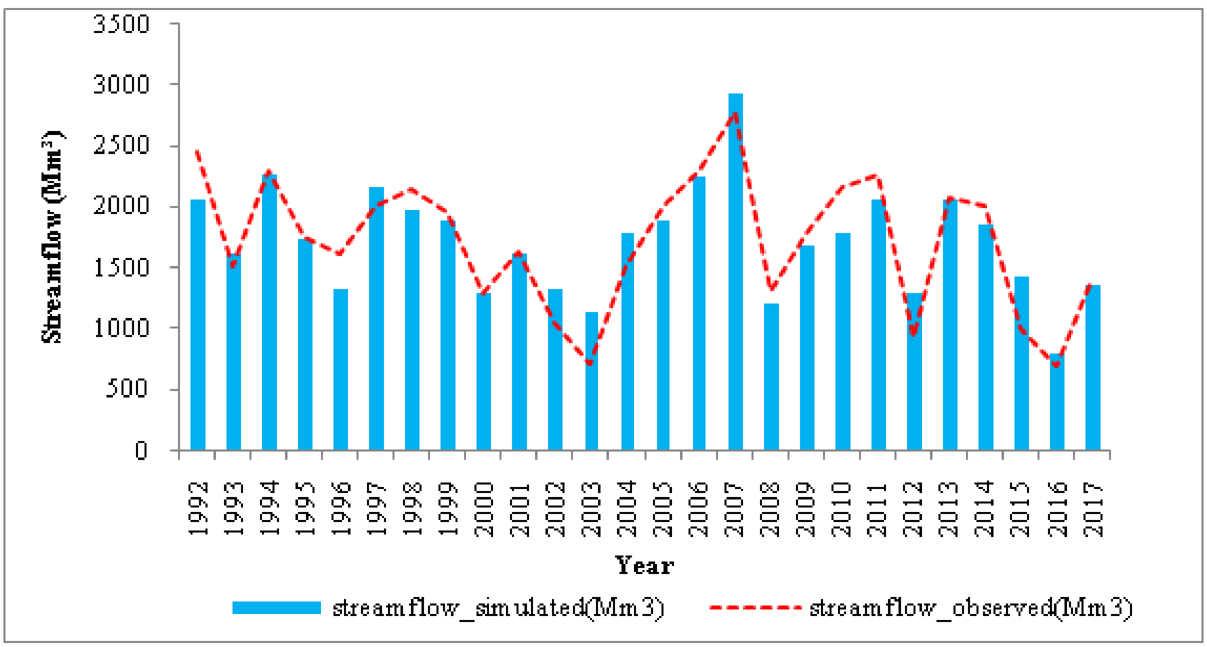

Fig 10. Observed and simulated streamflow at Pulamanthole during the entire simulation period

of the model for Thuthapuzha region was done taking care of the different parameters affecting the hydrology of the region. The developed model can be used for further studies in the same area including climate change and management impact analysis, land use change impact assessment etc.

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