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Performance of SWAT hydrological model of partially-gauged Nambul River urbanized catchment in Manipur IHR, India

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Abstract

Hydrological modelling of partially-gauged and ungauged catchments is vital for the better development of land and water management policies. The Nambul river catchment in Manipur, is partially gauged, so observed data is scarce. The objective of the study is to calibrate and validate the Soil and Water Assessment Tool (SWAT) model using remotely sensed surface soil moisture along with available streamflow data to improve the model's performance in simulating the hydrological functions as surface runoff, sediment yield, evapotranspiration, etc for a partially-gauged urbanized river catchment which is under stress. Using the Sequential Uncertainty Fitting, version 2 (SUFI-2) program built-in to SWAT-CUP, SWAT model was calibrated and validated on a monthly basis. Streamflow calibration is carried out with available measured data for the years 2000-2002 and validation for the year 2003. The soil moisture calibration period (2001-2011) and validation period (2012-2020) are also carried out sequentially. SWAT model calibration and validation using streamflow and surface soil moisture (ECMWF) showed good model performance with NSE of 0.65, 0.69, and 0.67, 0.71, and R^2 of 0.71, 0.74, and 0.70, 0.71, respectively. This study shows that remotely sensed satellite data can be used as one of the parameters and as an alternative to observed data for calibration and validation of the SWAT model of the Nambul river catchment. Further study, assessment, and management of the catchment can be aided by the study's contribution to hydrological modeling of ungauged or partially-gauged catchments where there is a scarcity of lack of routine observed hydrologic data.

Keywords: Remotely sensed, SWAT-CUP, SUFI-2, Surface runoff, Evapotranspiration, Sediment yield, R^2, Soil moisture, Nash-sutcliffe, *p*-factor, r-factor

1. Introduction

Hydrological modeling of partially-gauged and ungauged catchments is vital for development of land and water management policies. The calibration of parameters is imperative for implementing any study on hydrologic models. The hydrological models applied for the prediction of hydrological parameters depend on the quality of the model calibration. The hydrological cycle changes spatially and temporally; therefore, calibration and validation are necessary. The model parameters were selected for calibration such that they responded to watershed hydrologic components, such as runoff, evapotranspiration (ET), sediment yield, and water yield. The model parameters were fixed such that the simulated and measured data were closely approximated during the calibration process. Calibration is a process in which the parameters are fixed after several iterations such that the simulated values are close to the measured ones. Calibration and validation help in better simulation of hydrologic processes. The preference for objective variables in the process of model calibration and the resulting values of the parameters used strongly affect the simulated surface and subsurface flow fluctuations in hydrological modeling [1,2]. Hydrological modeling primarily focuses on the nature of the water cycle. The reliable study of the main components of the water cycle for resolving problems both quantitatively and qualitatively in water resource projects is streamflow. However, owing to the lack of routine gauging of catchments, there is scarcity of data. In recent years, regionalization techniques using remotely sensed satellite data have been used for parameter calibrations. Soil moisture is an important parameter in hydrological modeling as it controls streamflow estimation. Temporal variations and limitations can be substituted with spatial pattern-oriented model evaluation by inter-comparison of the remote sensing data-driven patterns of hydrological functions, such as ET and soil moisture, with simulated patterns using a hydrological model [3,4]. Model calibration and validation can be performed using different methods, namely i) concurrent and ii) step-by-step calibration. Multiple parameters are adjusted simultaneously in concurrent calibration. In the step-by-step calibration, parameters are adjusted separately for different hydrological components, such as surface runoff, ET, and soil moisture [5]. In this study, a continuous, physically based, semi-distributed hydrological model was used. Soil and water assessment tool (SWAT), a semi-distributed, continuous hydrological model that runs on a daily time basis and makes potential assessments of land use and climate change impacts on the hydrological regime of a watershed [6-11], was adopted in this study. The SWAT model is applicable for the estimation of various hydrological parameters of a watershed using input data, such as the digital elevation model (DEM), landuse land cover (LULC), and soil layer, derived using remote sensing and geospatial techniques [12,13,14]. The ability of the model to assess sediment, runoff, and nutrients based on different spatial data makes it a powerful tool for watershed studies. The Nambul River is one of the major rivers supplying water to Loktak Lake, the largest freshwater lake in north-eastern India. The Nambul River flows through the center of the urban area of Imphal. In the last decade, the Nambul River catchment (NRC) has been facing serious issues, such as declining surface runoff, sedimentation, and water pollution, due to deforestation, inappropriate agricultural practices, and rapidly increasing urbanization. The NRC lies primarily in the valley region of the Manipur Indian Himalayan Region (IHR), at an average elevation of 750-770m above mean sea level. In recent years, it has been frequently affected by floods because of its decreasing conveyance capacity and anthropogenic factors. Limited studies on the hydrological and hydraulic regime of Nambul River have been reported till date [15,16,17]. Extensive studies based on the hydrological database of NRC have not been conducted. The Nambul River is one of the active drainage channels of the Manipur River basin, conveying runoff flows from the upstream reaches to the agricultural fields located in the western valley region of Imphal, bypassing Imphal City as the major natural drainage channel, and finally discharging into Loktak Lake. It is imperative to understand the impacts of urbanization on the river hydro regime. Therefore, this study was undertaken to investigate the depleting hydrological processes in the NRC and the manner in which it affects the management of the river catchment. The objective of this study was to evaluate the performance of the SWAT hydrological model of NRC after calibration and validation using streamflow data and remotely sensed, spatially distributed surface soil moisture data to replicate hydrological functions, such as surface runoff or water yield, sediment yield, and ET. Despite the relative simplicity of SWAT model parameterization and implementation, its typical range of applications encounter considerable challenges, such as geospatial constraints in spatial resolution of the digital elevation model, when quantifying hydrological processes in environments with complex and urbanized catchments as NRC [20]. The novelty of this study lies in the calibration and validation of the SWAT model for better prediction of hydrological parameters under changing environments. The SWAT model will help to better study and manage water resources in partially-gauged and ungauged river catchments.

2. Materials and methods

2.1 Study area

Nambul River is one of the prominent rivers in the state of Manipur, which lies in the north-eastern *Purvanchal* Himalayan region of India, also termed as the "Manipur IHR" The Nambul River originates from Kangchup Hill in the western mountainous terrains of Manipur at an elevation of 1830 m above mean sea level and forms one of the major river catchments in the Manipur IHR. It has a main stream length of 62.70 km with minor tributaries, including Singda, Kharam, Lalli Khong, Luwangei, and Naga nalla streams, and comprises a catchment area of 217.38 km^2. The catchment is bounded by geographic co-ordinates of 23.80-25.68 °N latitude and 93.03-94.78 °E longitude, as depicted in Figure 1. The river flows through the densely populated Imphal urban and peri-urban areas before finally discharging into Loktak Lake at Yangoi Karong. The NRC is mostly occupied by agricultural land, apart from the inhabited areas. The people of Manipur rely on agriculture for their livelihood, the Nambul River has been a major source of irrigation water in the fields of Kadangband, Phumlou, and Lamshang.

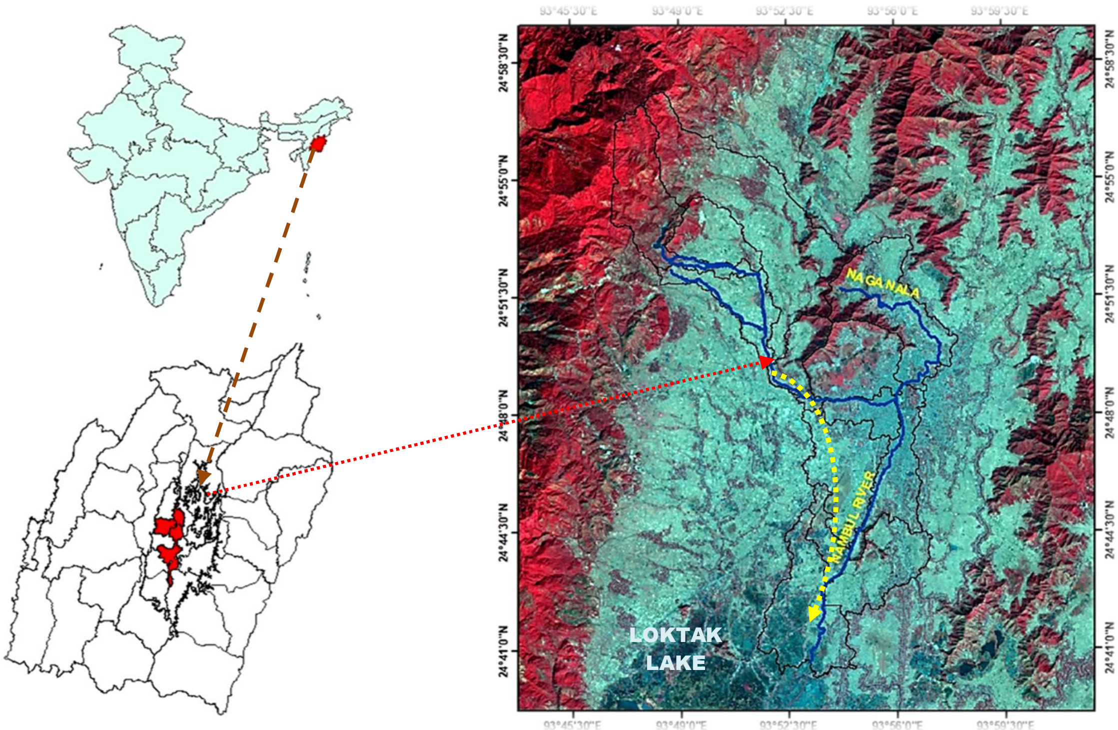

Figure 1 The Nambul River catchment and river system.

2.2 SWAT model description

SWAT is a continuous, semi-distributed simulation model that works on a daily, monthly, and annual basis. It utilizes land use layer maps, DEM, soil layer maps, and meteorological data as input data. The watershed is delineated using the DEM along with its stream network pre-definition option. Sub-basins and their corresponding hydrological response units (HRUs) were generated. HRUs contain unique characteristics of soil, land use, and slope. The SWAT model requires few hydrological parameters of the watershed and computes outputs, such as surface runoff, evaporation, and sediment yield, using the water balance relation to compute runoff and peak flows [7,8] as follows:

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

where, SW_0 denotes the initial soil water content, SW_t denotes the final soil water content, R_{day} denotes the daily precipitation, Q_{surf} denotes the surface runoff, E_a denotes the ET, W_{seep} denotes the loss to vadose zone, and Q_{gw} denotes the return flow.

The constraint in this study was the partial availability of data required for a comprehensive model study. The ground observed hydrologic–hydraulic data (1998-2004) was from the Loktak Development Authority (LDA) and the river gauge (water level) data (2017-2021) was from the Water Resources Department, Govt. of Manipur. (Table 1). Observed data collected from hydrographic surveys during 2020-2022 (Department of Science and Technology (DST)-Climate Change Programme (CCP)-HICAB Research project, International Convention for the Protection of All Persons from Enforced Disappearance (CED), National Institute of Technology (NIT) Manipur) were the main bases for SWAT model validation.

Table 1 Dataset used in SWAT model.

Sl. No	Dataset / Layer	GIS data class	Sources and resolution
1.	Land use Land Cover	GRID/Raster	SBIK, LISS-4 FX (2012), SENTINEL-2 MX, 10m (2020)
2.	Soil layer	GRID/Raster	National Bureau of Soil Survey and Land Use planning (NBSS&LUP); CAU (50K)
3.	DEM	GRID/Raster	CARTOSAT-1 Stereo derived,10m
4.	Rainfall, Temperature,and other climate data	ASCII/Excel/Text	ICAR (Lamphelpat, Imphal), Directorate of Environment and Climate Change, Govt. of Manipur
5.	River discharge	ASCII/Excel/Text	LDA (Loktak Development Agency (1998-2003); WRD, Govt. of Manipur

The NRC is primarily composed of agricultural land and settlement areas with rapidly propagating urbanization, as depicted by the LULC layer map in Figure 2. Only a small portion of the catchment consists of vegetation and forest, which are rapidly depleted as a result of rapid deforestation. Table 2 depicts the LULC statistics of the NRC, where agricultural land and settlement/urban areas cover the major portion.

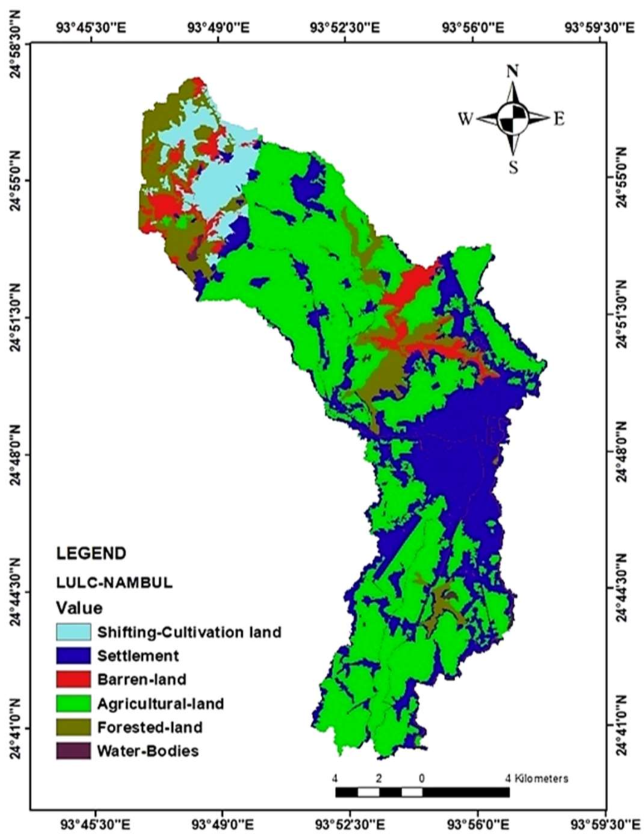

Figure 2 Land-use land-cover (LULC) map of the Nambul river catchment (2020, SENTINEL-2 MX derived).

Table 2 Land-use land-cover statistics of Nambul River catchment.

Land-use	Area [ha]	Area (km^2)	% Watershed area
Barren-land	826.961	8.270	3.8
Settlement/ Residential area	6653.285	66.533	30.59
Shifting cultivation area	932.755	9.328	4.29
Agricultural land	11112.060	111.121	51.09
Forest-mixed	1814.418	18.144	8.34
Water-bodies	408.685	4.087	1.88

The NRC consists of five main soil classes derived from the soil data of the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) (scale 1:250K), Central Agricultural University (CAU), and Imphal (1:50K), as shown in Figure 3. Table 3 shows the soil type and descriptions of the NRC.

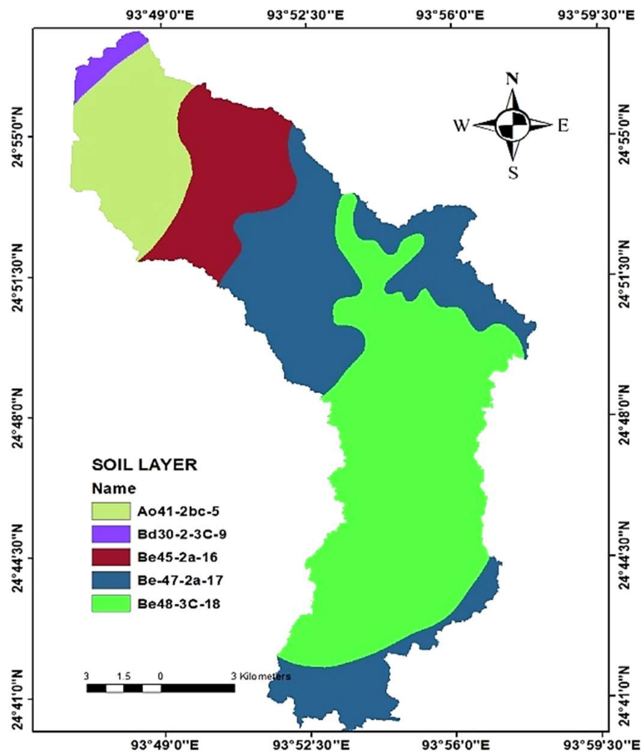

Figure 3 Soil layer map of the Nambul River catchment (derived from NBSS&LUP, CAU soil maps).

Table 3 Soil type description of Nambul River catchment.

Sl. No	SWAT soil code	Description
1.	Ao41-2bc-5	Clayey surface, well drained, moderate steep slope, moderate erosion.
2.	Bd30-2-3C-9	Loamy soil, excessive drained, moderate steep slope,severe erosion.
3.	Be45-2a-16	Clayey soil, poorly drained, Valley area, no erosion
4.	Be47-2a-17	Clayey soil, poor drained, valley, slight erosion
5.	Be48-3C-18	Fine loamy soil, poorly drained, valley area, no erosion

As most of the NRC is located in the valley region of Manipur, the catchment is characterized with ‘very gentle’ to ‘moderate steep’ slope with a small portion under ‘steep’ slope gradient.

2.3 Evaluation of SWAT model performance

To estimate the accuracy of the model, it is necessary to evaluate its performance. The Sequential Uncertainty Fitting version 2 (SUFI-2) programs inside the SWAT- Calibration and Uncertainty Programs (CUP) was used for model sensitivity analysis, calibration, and validation. The SUFI-2 program linkage with the SWAT model permits model simulation and control in iterative time steps and changes in model parameters [18-22]. The coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE) were used to determine the model performance in this study, with NSE as the objective function.

Nash-Sutcliffe efficiency is given by: $$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(Q_{obs}-Q_{sim})^2}{\sum_{i=1}^{n}(Q_{obs}-Q_{avr})^2} \quad (2)$$

Co-efficient of determination is given by: $$R^2 = \left[\frac{\sum(Q_{obs}-\overline{Q_{obs}})(Q_{sim}-\overline{Q_{sim}})}{\sum(Q_{obs}-\overline{Q_{obs}})^2 \sum(Q_{sim}-\overline{Q_{sim}})^2}\right]^2 \quad (3)$$

where I is the i^{th} observed value, Q_{obs} denotes the observed runoff, Q_{avr} denotes the average observed runoff over the entire study period, and Q_{sim} denotes the simulated runoff.

2.4 Uncertainty analysis

Uncertainty analysis was performed using the SWAT-CUP SUFI-2 program which predicts model uncertainty as a 95 percent prediction uncertainty (PPU) band [21]. The uncertainty of the model is provided by the r- and p-factors. The observed data percentage segregated by 95PPU is referred to as the p-factor, and the r-factor is the thickness of the 95PPU band [21]. A p-factor greater than 0.75 (range 0 to 1) and an r-factor close to 1 are considered good model performance values [21]. It has been found that the partitioning of uncertainty suggests that regional climate-based hydrological models contribute 40-62% to the uncertainty in streamflow projections [20,21,22]. This study attempted to find a better analogy of 95PPU.

3. Results and discussion

The NRC comprises13 sub-basins (Figure 1), for which 13 HRUs were generated based on LULC, soil class, and slope, with a threshold value of 50%. The various hydrological components were simulated on a monthly scale for the simulation years 2013-2020, followed by sensitivity analysis, calibration checks, and validation.

3.1 Analysis of sensitivity parameters

The process of determining how the target variables is affected by changes in other variables, referred to as input variables, is known as sensitivity analysis. Sensitivity analysis is an important step before model calibration to reduce the percentage uncertainty in the SUFI-2 program. For this study, 11 parameters were selected for calibration that relate to surface runoff, soil properties, river flow, and groundwater parameters, as presented in (Table 4).

We performed 1100 iterations for sensitivity analysis by adjusting the parameter ranges. The fitted parameters listed in Table 4 were obtained by iterating the previous set of parameter ranges. The significance of sensitivity is given by the p-value. A smaller *p*-value indicates a more sensitive parameter, whereas a larger *p*-value indicates a less sensitive parameter. The threshold water depth in the shallow aquifer for "revap" was taken as 41.75 (SWAT model range is 0-500) as the catchment is characterized by shallow groundwater profile. The results of the sensitivity analysis are shown in Figure 4.

Table 4 Parameter range used for SWAT model calibration.

Sl.No	Parameter Name	Fitted Value	Min-value	Max-value
1.	r_CN2.mgt	0.007800	-0.200000	0.200000
2.	v_ALPHA_BF.gw	0.001500	0.000000	1.000000
3.	v_RCHRG_DP.gw	0.180500	0.000000	1.000000
4.	v_REVAPMN.gw	41.750000	0.000000	500.000000
5.	r_SOL_AWC(..).sol	-0.136750	-0.250000	0.250000
6.	r_SOL_BD(..).sol	0.208250	-0.250000	0.250000
7.	r_SOL_Z(..).sol	-0.172750	-0.250000	0.250000
8.	r_SOL_K(..).sol	0.209250	-0.250000	0.250000
9.	v_CH_N2.rte	0.121650	0.000000	0.300000
10.	v_EPCO.bsn	0.151500	0.000000	1.000000
11.	v_ESCO.hru	0.965500	0.000000	1.000000

v_= existing parameter value is replaced by a given value, and r_= existing parameter value is multiplied by (1+ a given value).

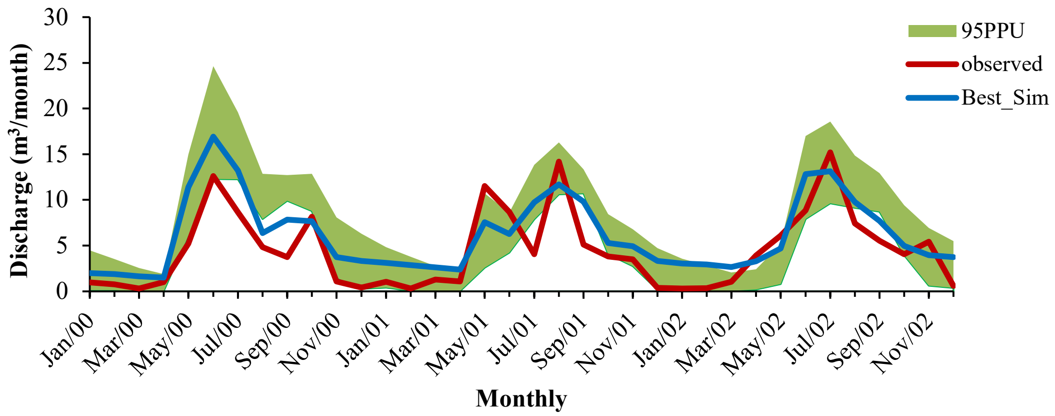

Figure 4 95PPU calibration plot using observed values of the Nambul River discharge.

Table 5 shows that the parameters of the groundwater percolation factor (RCHRG_DP) and soil conservation service (SCS) runoff curve number (CN2) have a near-zero *p*-value; baseflow alpha factor (ALPHA_BF) and saturated hydraulic conductivity (SOL K) have the smallest *p*-values. Therefore, these four parameters were the most sensitive for the NRC. The most sensitive parameter affects the calibration and validation of the model; however, there is no effect of variations in the other parameters.

Table 5 Global sensitivity analysis for 11 parameters of Nambul catchment.

Name of parameter	t-Stat	*p*-value
v_EPCO.bsn	-0.818706264	0.413133302
v_REVAPMN.gw	-0.902254832	0.367121209
v_ESCO.hru	-0.998785607	0.318120638
r__SOL_Z(..).sol	-1.002158781	0.316489740
v__CH_N2.rte	1.478281913	0.139621765
r_SOL_AWC(..).sol	-2.222695179	0.026441294
r_SOL_BD(..).sol	-2.799270305	0.005212361
r_SOL_K(..).sol	-2.902086509	0.003781588
v_ALPHA_BF.gw	-3.785476730	0.000161792
r_CN2.mgt	-14.907708840	0.000000000
v_RCHRG_DP.gw	32.921761311	0.000000000

*Smaller *p*-value indicates more sensitivity parameter.

3.2 Streamflow calibration and validation

The SWAT model run was executed for 23 years, starting from 1998 to 2020, in which two years were used as the warm period. No simulation was carried out for the warm-up period. Calibration was performed with 1100 simulations using observed discharge data at Hiyangthang gauge station (source: LDA) for the period of 2000-2002 and validation was performed for one year (2003) on a monthly time scale at the outlet of the catchment. The parameter range was adjusted to match the observed and simulated soil moisture according to the sensitivity analysis. In the calibration process, an NSE of 0.65 and an R^2 of 0.71 were obtained. The NSE and R^2 for the validation period were 0.67 and 0.74, respectively. The SWAT model showed an acceptable range of values during both calibration and validation (Table 6).

Table 6 Statistical summary for calibration and validation of discharge (performed using SUFI-2) for NRC.

Steps	NSE	R^2	*p*-factor	r-factor
Calibration	0.65	0.71	0.9	0.69
Validation	0.67	0.74	0.86	0.52

Several studies demonstrated good model performances within acceptable values of NSE>0.6 and R^2>0.7 Studies [2,4,5] used long-term observed discharge data for the calibration and validation processes. However, limited observed discharge data were used in the present study for model calibration and validation, resulting in an acceptable NSE >0.5 and R^2>0.7. CN2, which is a major parameter affecting runoff, was found to be the most sensitive parameter for discharge calibration.

3.3 Surface soil moisture calibration and validation

Calibration was performed using 11 selected parameters by iteratively adjusting the parameter range. The process was carried out using remotely sensed surface soil moisture data [22] from the European Center for Medium-Range Weather Forecasts (ECMWF) Copernicus Climate Change Service. The ECMWF soil moisture data are in a global grid format, with a resolution (0.25°× 0.25°), and over a long period, that is, from 1978 to the present date. However, because the study area had only one station for obtaining climate data, a single grid value was used for calibration and validation purposes. The SWAT model calibration was conducted for the period of 2001-2011 and validation for the period of 2012-2020 in terms of the simulation period. The calibration and validation plot obtained are shown in Figure 5 and Figure 6.

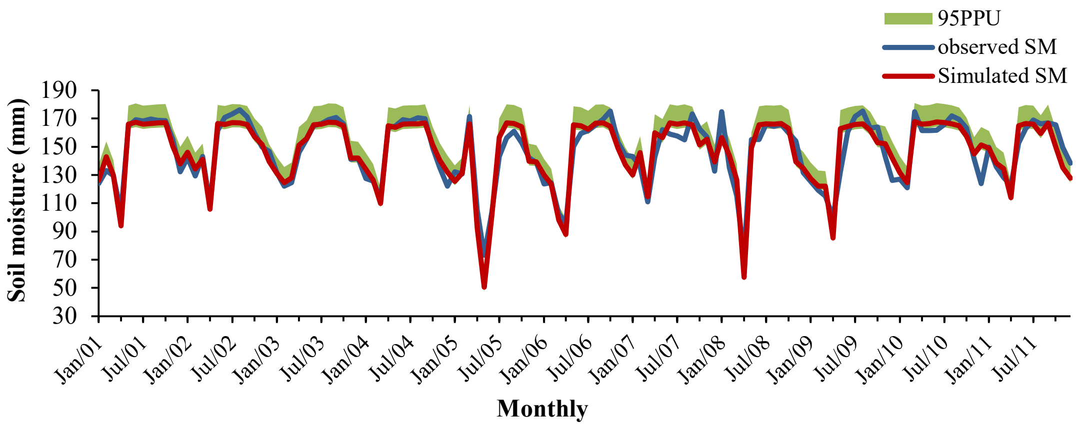

Figure 5 95PPU calibration plot using soil moisture data (from ECMWF).

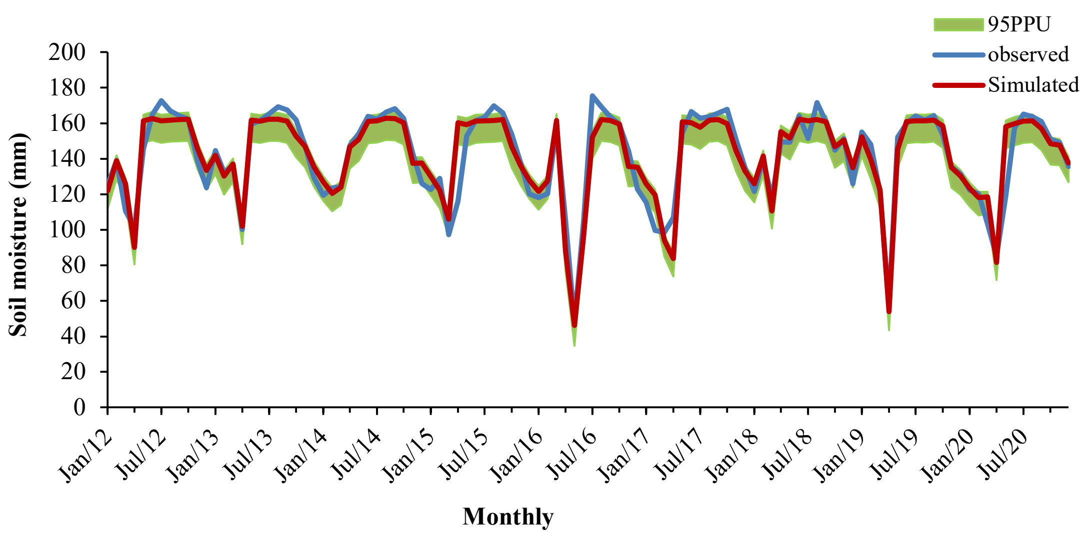

Figure 6 95PPU validation plot using soil moisture (from ECMWF).

In the calibration, a p-factor of 0.90 and an r-factor of 0.68were obtained (Table 7). Since the p-factor is greater than 0.7, and the r-factor is less than 1.5, model calibration can be termed as good. The same range of calibration parameters was used to validate the SWAT model. The validation was conducted from 2012 to 2020 on a monthly basis at the sub-catchment level.

Table 7 Statistical summary for calibration and validation of soil moisture (performed using SUFI-2).

STEPS	NSE	R^2	*p*-factor	r-factor
Calibration	0.69	0.70	0.90	0.68
Validation	0.71	0.71	0.92	0.59

During the validation process of the SWAT model with respect to soil moisture, NSE values of 0.71 and R^2 of 0.71 as show in Table 7 were obtained, implying good model performance. An output *p*-factor of 0.92 and an r-factor of 0.59 indicated an acceptable correlation between the observed and simulated soil moisture parameters.

The SWAT model provided outputs, such as surface runoff (SURFQ), ET, potential evapotranspiration (PET), and sediment yield (SYLD), for the simulation period of 2013-2020 carried out without any calibration, as presented in Figures 7A and B. After the recursive analysis and calibration checks were performed on the applied SWAT model, a final simulation run was carried out for the NRC SWAT hydrological model to derive the hydrological functions, which are presented in Figures 8A and B.

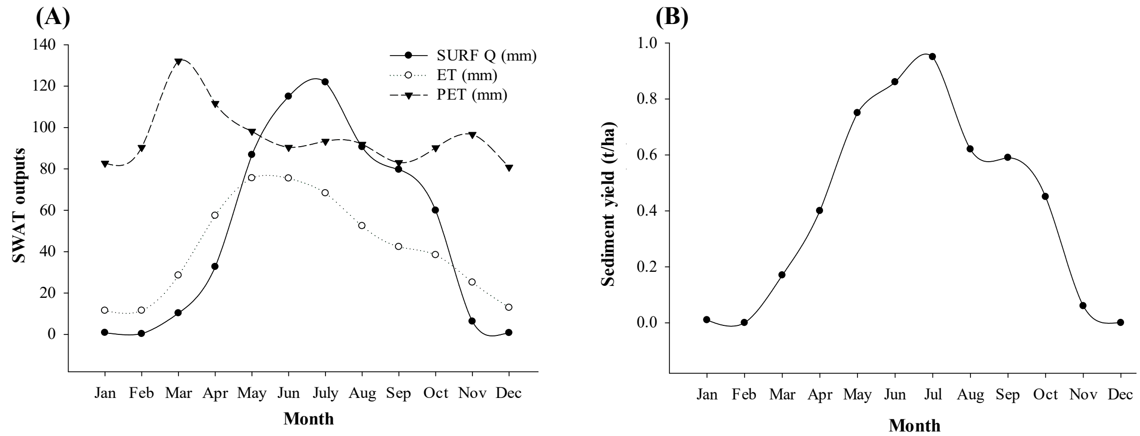

Figure 7 (A) Hydrological parameters obtained from uncalibrated SWAT model (monthly averaged 2013-2020) and (B) Sediment Yield obtained from uncalibrated SWAT model (monthly averaged 2013-2020).

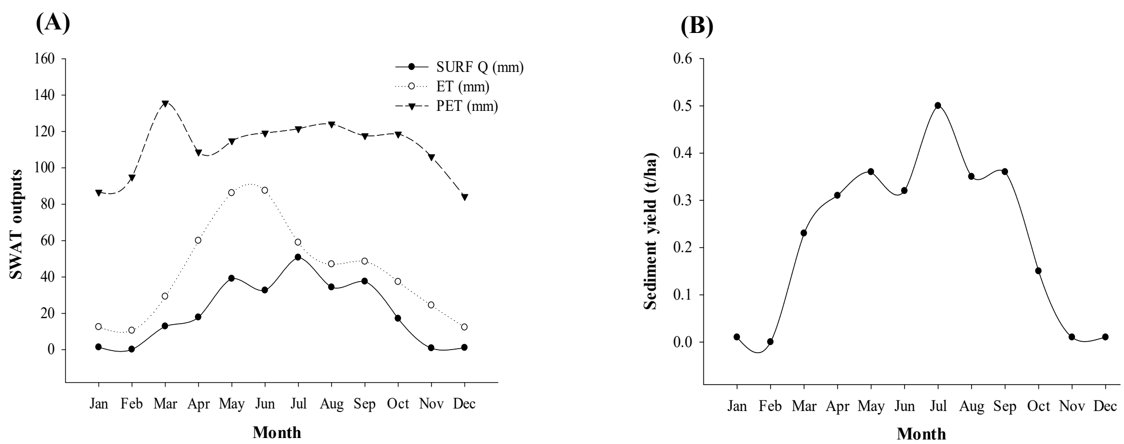

Figure 8 (A) Hydrological parameters obtained from calibrated SWAT model (monthly averaged 2013-2020) and (B) Sediment Yield obtained from calibrated SWAT model (monthly averaged 2013-2020).

It is observed (Figures 7A and 8A). that there is sharp decrease in the computed monthly-averaged annual surface runoff (SURF_Q) peak value of 125 mm from the uncalibrated SWAT model to 50 mm from the calibrated SWAT model. Similarly, the computed monthly-averaged annual sediment yields peak value (SED_YLD) decreases from about 0.95 to 0.50 t/ha as a result of the calibration performed on the SWAT model, as observed from Figures 7B and 8B. This is a realistic result, as physically based hydrological models tend to overestimate surface runoff without proper calibration [11,18,22]. However, peak value of monthly-averaged annual actual ET was computed from approximately 77 to 92 mm (after) the SWAT model calibration, as observed from Figures 7A and 8A. The peak sediment yields as well as the peak runoff occurred in the monsoon month of July. ET is found to peak in between the months of May to June, which lags the PET which shows a peak in the month of March. Thus, it can be concluded that the use of remote sensing data and associated products used in this study to overcome several current limitations of hydrologic modeling imposed by data constraints would lead to a realistic simulation of hydrologic processes [22], particularly in ungauged or poorly gauged catchments as the NRC.

4. Conclusion

The results from the multi-year monthly-averaged SWAT model calibration and validation demonstrated the effectiveness of incorporating gridded soil moisture into hydrological assessment models within the Purvanchal Indian Himalayan region. By modifying the parameter ranges in the SUFI-2 algorithm, the uncertainty margin between the observed and simulated data was minimized. SWAT model calibration and validation using the available measured flow data gauged at Hiyangthang, showed an acceptable NSE of 0.71 and R^2 of 0.71 for effective model performance. Four parameters viz., RCHRG_DP, CN2, ALPHA_BF, and SOL K, were found to be the most sensitive parameters for the low gradient urbanized NRC. Apart from the sensitive parameters, the other parameters had no effect on the calibration and validation of the model. The surface runoff decreased in the calibrated model by approximately 75 mm, as the CN2, RCHRG_DP, and ALPHA_BF parameters were sensitive and had their respective effects on the hydrological outputs. As a result, the SWAT model can be considered suitable for further studies on hydrological parameters such as surface runoff, water and sediment yield, ET, and PET. Additionally, it may be deduced that remotely sensed satellite data can be used for the effective calibration and validation for an ungauged or partially-gauged urbanized catchment such as the NRC.

5. Acknowledgements

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