Simulating hydrological responses using high resolution satellite inputs for a forest dominated hilly catchment of Uttarakhand Himalayas

Article *in* Arabian Journal of Geosciences · June 2023

DOI: 10.1007/s12517-023-11505-y

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Arabian Journal of Geosciences (2023) 16:401
https://doi.org/10.1007/s12517-023-11505-y

ORIGINAL PAPER

Simulating hydrological responses using high resolution satellite inputs for a forest dominated hilly catchment of Uttarakhand Himalayas

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Received: 31 January 2023 / Accepted: 20 May 2023

Abstract

Waterscarcity in hilly region has been increasing due to unprecedented population growth, rapid urbanization, industrialization, and various anthropogenic activities. Hence, there is urgent need of accurate estimation of streamflow at river basin scale. Regardless, many hydrological models exist in hydrology, but their capability over hilly river basin is found to be poor, often because of lack of good-quality data over the region. The study undertaken presents an evaluation of widely accepted Soil and Water Assessment Tool (SWAT-2012) model for simulating stream flow in a forest dominated catchment of Kumaon region of Himalayas. SUFI-2 algorithm was used for performing calibration and validation analyses. The model is applied for a duration of 15 years (2000–2013) with 2 years (1998–1999) as warm-up period, 2000–2010 as calibration, and 2011–2013 for validation. During the calibration period of 11 years (2000–2010), the model showed coefficient of determination (R^2) and Nash–Sutcliffe Efficiency (*NSE*) values of 0.72 and 0.7, respectively. Similarly, over the 3 years (2011–2013) during validation, the value of R^2 and *NSE* were 0.7 and 0.67, respectively. Sensitivity analysis for 12 input parameters which affect streamflow was carried out, and ranking was done on *p* value leading to the most important parameter affecting the streamflow. This study may be utilized as a decision-making tool by water managers to influence strategies in the management of watershed processes.

Keywords Calibration · Sensitivity analysis · SWAT model · Himalayan region · Uttarakhand

Introduction

Water is one of the most important natural resources for living things on the Earth. Accurate estimation of stream flow has emerged a challenging task particular in hilly region, where there is paucity of availability of good quality data (Kumar et al. 2021a, b, 2023a). Many hilly catchments in central Himalayan region (CHR) are forest dominated (Tyagi et al. 2014). Various studies (Qazi et al. 2012; Chauhan et al. 2017; Qazi et al. 2017; Qazi and Rai 2018; Shayannejad et al. 2022; Ostad-Ali-Askari 2022) suggest that forests play a pivotal role in hydrological response of catchment located in CHR. Unfortunately, because of rapid urbanization, population growth, dam construction, as well as climate change and anthropogenic activities, these forests are under severe stress leading to affect the hydrological response of catchment located in Himalayan region. The different components of hydrological cycle such as infiltration, ground water recharge, soil moisture, and evapotranspiration are affected by anthropogenic activities and climate change, which in turn affect the basin water resources (Kumar et al. 2022; Kumar et al. 2023a). Hence, there is urgent need for simulating water resources with reasonable accuracy.

From the review of literature, it can be found that significant research related to rainfall-runoff modelling has been done in different catchments all over country, but very limited studies have done in hilly catchment of Kumaon

Responsible Editor: Broder J. Merkel

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region. Furthermore, no studies have been done on simulating streamflow of Kosi river basin in Kumaon region. Himalayan region is considered as water tower as it serves water to 20% population of the world. The hill of Himalayan region plays a remarkable role in climatology of country as they bring monsoon to the country. This region is recognized as one of the most sensitive places in the planet to climate change and is also facing more warming than the world average. This region is experiencing variability in precipitation along with extreme event and shrinking of glacier. These recent impacts due to climate change during recent decade have prominent effect on glacier and water resources in Himalayan region. Therefore, there role is vital for water resource planning and management. Numerous hydrological models exist in hydrology for precise estimation of stream flow, but process-based model was found to be more useful due to explicit representation of rainfall runoff process in physics-based term. Among different process-based hydrological models, Soil and Water Assessment Tool (SWAT) is the most widely accepted for simulating stream flow. The most important property of the model is that it operates on hydrological response unit (HRU). It is the smallest spatial entity of the model which has same combination of soil, land use/land cover (LULC), and slope within a catchment. Due to multifaceted capability and several inbuilt hydrological feature, SWAT is widely applied in different domain of hydrology and water resource studies such as simulation of runoff, sediment and nutrient load, understanding the impact of climate change and LULC, non-point source pollution, selection of best management practices, and impact on stream flow/ground water. However, the prime focus of this study is on applicability of this model for simulating streamflow for hilly catchment.

The Kosi river basin (KRB) is a major river basin in Kumaon division Uttarakhand, characterized by undulating topography, high population density, and rapid urbanization in recent years. However, the region is prone to frequent and devastating floods due to the uneven spatial–temporal distribution of rainfall. The water of KRB is being used for various purposes such as drinking, washing, and bathing. No studies have been done to apply and test the efficacy of SWAT model for simulating hydrological flux to understand the hydrological behavior of the basin.

In the light of all the aforementioned issues, the aim of this study is to test the efficacy of SWAT model for simulating stream flow and to perform sensitivity analysis for a forest dominated Kosi river basin in Kumaon region of Uttarakhand, since no study has been conducted on hydrological simulation till now. This study will be a new kind of study to understand the hydrological interaction operating in Himalayan ecosystem.

Study area and data used

Kosi river basin lies in the Kumaon region of Uttarakhand and has geographical extent of 29° 18′ N–79° 02′ E and 29° 51′ N–79° 51′ E, respectively (Fig. 1). The elevation of the basin ranges from 356 to 2733 m above mean sea level (MSL).

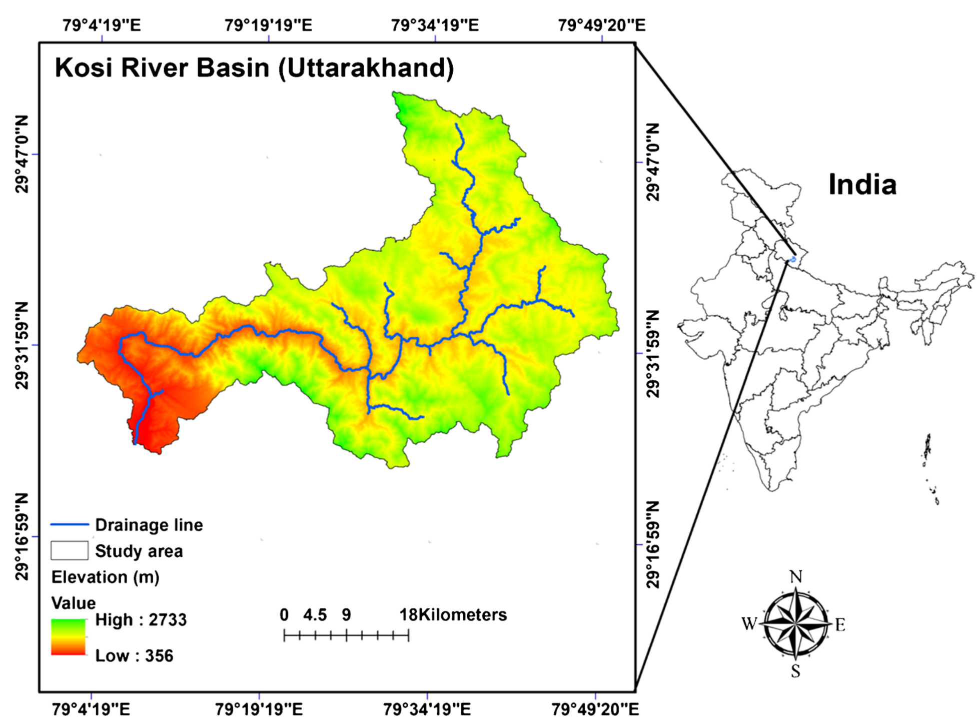

Fig. 1 Location of the study area showing topography of the study area

Being a mountainous region, topography of the region is of mixed type (extremely hilly and rolling) and major portion of the basin lies under steep slopes. The study area is described by highly folded and faulted chain of Kumaon hills. Climatic parameters significantly vary along the basin. The annual rainfall over the study area varies in the range of 850 to 1100 mm. The climatology of the study area is characterized by humid, sub-temperate climate sub-tropical with mean annual temperature of 19.8 °C. The drainage density in hilly part of the basin is higher, while it is moderate in lower slopes of the basin. The basin exhibits trellis and dendritic type of drainage pattern. Soils are acidic in nature having pH between 4.5 and 6.5 and can be categorized under hydrologic soil groups B and C. Broadly, the texture of the soils can be classified as fine loamy to coarse loamy. Depth of soil varies from shallow to deep and slope varies from gentle to very steep. The watershed is rich in forest resources and dominated by pine trees (*Pinus*) and oak (*Quercus*). Main crops grown in the study area are wheat, paddy, barley, pulses, and vegetables. The climate and vegetation vary greatly with elevation, from glaciers at the highest elevations to subtropical forests at the lower elevations.

Methodology

Data used

Physiographic and hydro-meteorological inputs are required for rainfall runoff modelling using SWAT. The digital elevation model (DEM) is one of the important parameters for watershed delineation. Hydrological response units (HRUs) are derived from overlaying of three maps, land use/land cover, soil, and slope. The Shuttle Radar Topography Mission (SRTM) DEM is used for watershed delineation. Several studies have been conducted to ascertain the accuracy of this DEM with globally available DEM. Precipitation, temperature (maximum and minimum), wind speed, relative humidity, and solar radiation are all required meteorological inputs for the SWAT model. Daily India Meteorological Department (IMD) gridded observation datasets of precipitation rainfall and temperature available freely having spatial resolution of 0.25°×0.25° and 1°×1°, respectively, were downloaded from National Data Centre, Pune (Table 1). Observed data for wind speed solar radiation and relative humidity were obtained from SWAT website (http://globalweather.tamu.edu/). It is suggested to use actual/observed precipitation data since it is most important factor for hydrological modelling. Observed streamflow data for whole simulation period is required calibration and validation of the model. Harmonized World Soil Database (HWSD v1.1) developed by Food and Agriculture Organization of the United Nations (FAO-UN) which contains two-soil layer information from 0 to 30 cm and 30–100 cm depths was utilized in the study.

Table 1 Description and sources of data used in SWAT model

Data used	Data sources	Data resolution
MaxT, MinT, RF	IMD gridded data	RF (0.25×0.25 degree), temp (1×1 degree)
LULC map	ESA CCI[a] land cover map	10 m
SRTM DEM	SRTM official website	30 m

[a]European Space Agency Climate Change Initiative

SWAT model

The Arc-SWAT model is a semi-distributed hydrological model that is integrated into an ArcGIS interface. It includes various components such as hydrological, sedimentation/erosion, weather, plant growth, nutrients, land management, channel routing, and pond/reservoir routing. However, for this study, only the hydrological, weather, and channel routing components were utilized (Yu et al. 2018; Du et al. 2019; Eini et al. 2019, 2020; Hosseini and Khaleghi 2020). The model calculates the water cycle using the water balance equation:

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

where SW_t is the final soil water content, SW_0 is the initial soil water content, t is time in days, R_{day} is the amount of precipitation, Q_{surf} is the amount of surface runoff, E_a is the amount of evapotranspiration, W_{seep} is the amount of water entering the vadose zone from the soil profile, and Q_{gw} is the amount of return flow. All are expressed in millimeters.

The SWAT is a process-based model used to assess the impact of land management practices on water, sediment, and chemical yields in agricultural watersheds. It can be applied to watersheds with varying soils, land use, and management conditions over a long period, making it a flexible and efficient tool for evaluating changes in land use and management practices. SWAT offers two computational methods for estimating surface runoff: the Soil Conservation Service (SCS) Curve Number method and the Green and Ampt technique (1911). The variable storage method was used to route flow in channels, while the modified Penman–Monteith method was applied to determine potential evapotranspiration.

SWAT model simulation steps

SWAT is semi distributed process based basin scale hydrological model (Arnold et al. 1998). It is robust and efficient in simulation for long period for varied range of watersheds (Gassman et al. 2007). The entire process of SWAT-based hydrological modelling approach is shown in Fig. 2. SWAT-based hydrological modelling approach involves following important process: (1) SWAT project setup, (2) delineation of watershed, (3) HRU analysis (4) writing and editing of table, (5) execution of model, (6) calibration and validation of model. ArcSWAT is incorporated in the ArcGIS environment to execute SWAT model.

SWAT (2012) model was integrated with ArcGIS (10.4) to explicitly allow the inclusion of spatial data. The different inputs, viz., digital elevation model, land use, soil map, and slope map, were converted into grid raster format and then re-projected to the Universal Transverse Mercator (WGS_1984_UTM_Zone_46 N). The first step in the project setup is to specify a directory which includes all the necessary databases and folders to store the data. The second step is catchment delineation; a threshold is fixed to delineate sub-watershed. After delineation of watershed, all the geospatial inputs (LULC, soil and slope maps) were overlaid to create HRUs. According to Ricci et al. (2018), threshold values of 5%, 10%, and 10% were used for land use, soil, and slope classes, respectively, to eliminate minor classes for modelling 100% of land area in the sub-basins. The outlet of the basin falls in the sub-basin 25 with a total contributing area of 1845 km^2. Therefore, SWAT is a semi-distributed model which operates at HRU level.

Following the creation of HRUs process, the weather input file is prepared using India Meteorological Department (IMD) and SWAT tamu data. Weather input file was written into the model, and database is updated. After input of all meteorological data, the model is executed and result is simulated. The output of the model is the default simulation; it does not produce satisfactory result. Hence, the model is calibrated and validated with respect to observed hydrologic data. Calibration is performed to identify the parameters which mimics the hydrological process of the catchment and their optimum parameter value to build most suitable model structure to the local hydrologic condition.

Calibration and validation

SWAT parameters play a crucial role in the accuracy of the model simulations. A sensitivity analysis was performed to identify the most appropriate parameters for a given

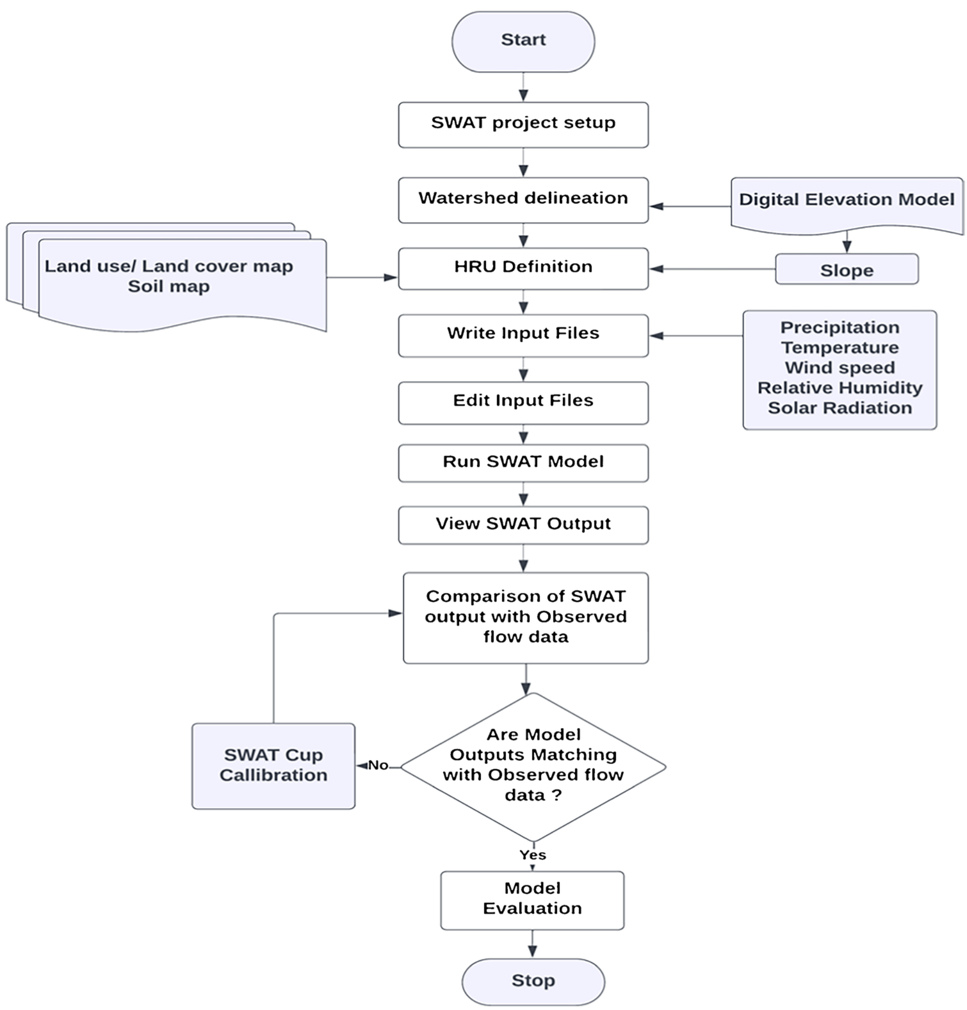

Fig. 2 Flowchart showing the step-by-step process of SWAT-based modelling

watershed, either through changing one parameter value at a time or using the SWAT-CUP tool. The Nash–Sutcliffe Efficiency (*NSE*) is selected as the objective function for model calibration. Several authors have recommended *NSE* as one of the most important tools for checking model accuracy (McCuen et al. 2006; Moriasi et al. 2015). The calibrated model was then validated against observed discharge data using manual or automated calibration methods. This approach ensures that the model is within a realistic uncertainty range and can accurately simulate future conditions. The calibration process is accomplished using SWAT-Calibration and Uncertainty Procedures (SWAT-CUP) software, which is used for the auto-calibration of the SWAT-simulated flows (Abbaspour 2014). Manual calibration is also performed by checking the influence of individual parameters values on the model and finding their suitable value by repetitive trials. The approach of changing one parameter value at a time during sensitivity analysis, while computationally less demanding, has many drawbacks. It is more time-consuming and makes it hard to track inter-parameter sensitivity, such as the sensitivity of one parameter through a range in value of another parameter. In the case of automatic calibration approach using the SWAT-CUP optimization tool, where multiple runs (usually 500–1500 runs) are generated with randomly selected parameter values to eliminate the drawbacks of manual calibration. However, this approach has drawbacks such as the cost of licensed use, time required for analysis setup, and higher computational requirements. However, if a set of sensitive parameters were available along with value ranges for similar regions, manual calibration may be a relatively easier option. There are different types of algorithms inbuilt in SWAT-CUP, among which, the most popular sequential uncertainty fitting (SUFI2) tool is applied in this study. The model is validated to authenticate its applicability over the study area.

Performance statistics

By using both graphical and statistical methods, the study can identify any systematic biases or errors in the model's output, as well as any variability that may be present. To determine the efficacy of model performance to evaluate hydrological behavior (i.e., streamflow), statistical parameters such as the coefficient of determination (R^2), *NSE*, and root mean squared error (*RMSE*) along with visual hydrographs were selected as recommended by Moriasi et al. (2007) and Krause et al. (2005). R^2 shows how strong the linear relationship among measured and predicted value of a variable. *NSE* represents a normalized value that describes the relative magnitude of the residual variance compared to observed data set variance. *RMSE* shows the measure of mean residual variance. The value of *NSE* may range from $-\infty$ to 1, whereas R^2 value ranges from 0 to 1. The perfect value of both *NSE* and R^2 is 1, which represents an ideal match of model outputs with the actual/observed data. *NSE*, R^2, and *RMSE* were computed using Eqs. (2), (3), and (4), respectively.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} \left(Q_i^{Obs} - Q_i^{Sim}\right)^2}{\sum_{i=1}^{n} \left(Q_i^{Obs} - \overline{Q_i^{Obs}}\right)^2} \right] \tag{2}$$

$$R^2 = \left[\frac{\sum_{i=1}^{n} \left(Q_i^{Obs} - \overline{Q_i^{Obs}}\right)\left(Q_i^{Sim} - \overline{Q_i^{Sim}}\right)}{\sqrt{\left(Q_i^{Obs} - \overline{Q_i^{Obs}}\right)^2 \left(Q_i^{Sim} - \overline{Q_i^{Sim}}\right)^2}} \right]^2 \tag{3}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(Q_i^{Obs} - Q_i^{Sim}\right)^2}{n}} \tag{4}$$

where Q_i^{Obs}, Q_i^{Sim}, $\overline{Q_i^{Obs}}$,$\overline{Q_i^{Sim}}$, and n represent the observed, simulated, mean of observed values, mean of simulated values in respective time steps i, and the total number of observations, respectively.

Results and discussions

SWAT model data pre-processing

Hydrological modelling was carried out over Kosi river basin using high resolution satellite imagery. The slope map derived from DEM of Kosi river basin is presented in Fig. 3c. It is depicted from Fig. 3c that majority of catchment area falls under steep slope categories. The catchment area is divided into five categories based on slope characteristics. The LULC map of catchment is shown in Fig. 3d. Kosi river basin is classified into five major classes based on LULC classification.

The false colour composite map of KRB Catchment is shown in Fig. 3a, while corresponding normalized difference vegetation (NDVI) map, which is derived from Sentinel imagery, is represented in Fig. 3b. It can be clearly depicted that the highest value of NDVI during was 0.82 and the lowest NDVI was − 0.42. The NDVI of upper (northern) portions is mostly positive, which represents green cover. These areas are mostly covered by rock or snow. The negative NDVI representing reservoir and rock is mostly found in lower (southern) portions of the catchment. These results are in accordance with the LULC classified map presented in Fig. 3d. The catchment area is covered by two types of soil, and their properties are given in Table 2.

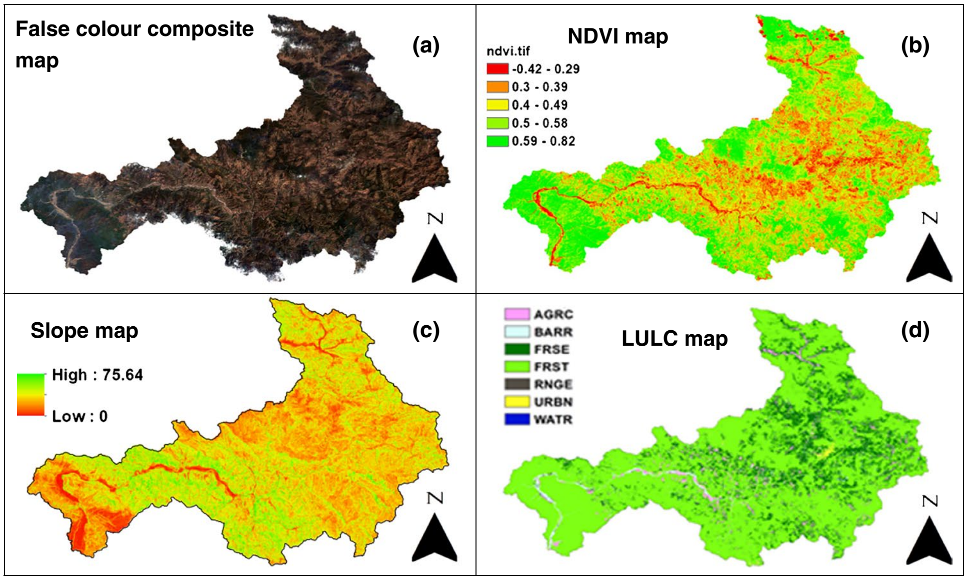

Fig. 3 Study area: **a** false color composite map, **b** NDVI map, **c** slope map, and **d** LULC map over Kosi river basin

Calibration and validation

The SWAT model provides different outputs at each sub-basin, but the major aim of this study is the streamflow at the outlet of entire catchment, as the observed streamflow data is available. The outlet of entire basin lies in sub-basin 25 with total contributing area of 1845 km^2. The discharge provided by SWAT for sub-basin 25 is used for calibration with available observed data. A split sample procedure using monthly discharge measured at the outlet of the basin for the period 2000–2010 and 2011–2013 was used for calibration and validation, respectively. The first 2 years from 1998–1999 were used as a warm-up period to alleviate unknown initial condition. The warm-up period is used to carry out initial soil–water balance for model simulation. (Pandey et al. 2021). In other words, the warm-up of a model is defined as it is adjustment process for putting the model in an optimal state such that the internal stores (e.g., soil moisture) reach an optimal state (Kim et al. 2018). The model is then validated with observed flows for the period 2011–2013. To check the efficiency of a model based on visual assessment, plots were drawn between monthly observed and simulated discharge for KRB as shown in Fig. 4. Visual assessment of these plots shows that the simulated discharge was generally lower than the corresponding observed discharge data during periods with concentrated flow. Nonetheless, the correlation of observed and simulated values of discharge showed outstanding results for calibration and validation periods. The result found is in line with recent studies conducted by Dash et al. (2020) and Gull and Shah (2022). The SWAT-CUP known as SUFI-2 was used to calibrate and validate the model as the procedure described in the User's Manual (Winchell et al. 2010) with an aim to achieve good model performance by of reducing *RMSE* between observed and simulated runoff while maximizing *NSE* (Nash–Sutcliffe Efficiency). The range for different performance parameters was taken from Stehr et al. (2010). Interested reader can find the detailed description of these parameters and their importance from the SWAT website (https://swat.tamu.edu/) in addition to the previously cited studies. Detailed procedures were followed during manual calibration for selection of sensitive parameter and their corresponding range. The parameters selected during calibration with default and calibrated values are given in Table 3.The observed and simulated discharge values were plotted against one another to decide the goodness of fit criterion of R^2 and *NSE* for discharge. Statistical comparison of monthly discharge result showed good agreement with monthly observed values (Fig. 5; Table 4). However, in some years, the model clearly overestimated the streamflow. The model output is more correlated to rainfall, which is an indication of good hydrological modelling.

Sensitivity analysis

The first step towards a better comprehension of the SWAT model is to identify a set of critical parameters, which have a significant impact on model outputs. Sensitivity analysis

Table 2 Van Genuchten–Mualem model parameters derived using the ROSETTA model

FAO soil class (texture)	θ_s(cm^3/cm^3)	θ_r(cm^3/cm^3)	n_p(-)	A(cm^{-1})	k_s(cm/day)
Bd29-3c-3661 (clay loam)	0.41	0.095	1.31	0.019	6.24
Be72-2c-3671 (loam)	0.43	0.078	1.56	0.036	24.96

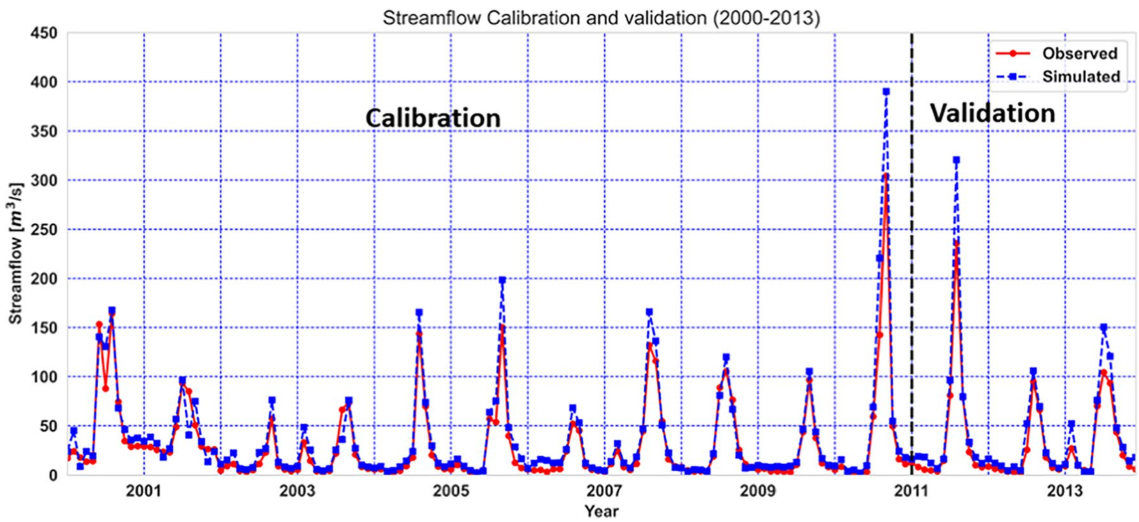

Fig. 4 Results of observed and simulated streamflow during calibration and validation period

Table 3 The parameters considered their range and best fitted value obtained through SWAT calibration

Sr. no	Parameter_Name	Fitted_Value	Min_value	Max_value
1	R__CN2.mgt	−0.125	−0.25	0.25
2	V__ALPHA_BF.gw	0.75	0	1
3	V__GW_DELAY.gw	342.5	20	450
4	V__GWQMN.gw	1250	0	5000
5	V__CH_K2.rte	36.25	5	130
6	R__SOL_ AWC(..).sol	−0.05	−0.2	0.4
7	V__ESCO.hru	0.75	0	1
8	V__RCHRG_DP.gw	0.75	0	1
9	V__CH_N2.rte	0.0625	0.01	0.08
10	R__SOL_K(..).sol	−0.4	−0.8	0.8
11	R__HRU_SLP.hru	0.15	0	0.6
12	V__ALPHA_BNK. rte	0.125	0	0.5

was performed to determine the most appropriate parameters for a given watershed. A set of parameters controlling streamflow were chosen based on extensive relevant literature (Worku et al. 2017; Afshar and Hassanzadeh 2017; Markhi et al. 2019) and SWAT documentation (Neitsch et al. 2005). In this study, a global sensitivity analysis method (one-at-a-time) was applied to identify the most dominant variables of the model and their relative sensitivity. The SUFI-2 algorithm utilized sensitivity analysis to identify the 12 most sensitive parameters for streamflow. Table 3 presents a summary of the sensitive parameters identified through sensitivity analysis in the SUFI-2 algorithm, along with their rank and fitted values. The effects of the selected parameters on model performance are presented in terms of dotty plots in Fig. 6. The X-axis represents the value of the parameter, and the Y-axis shows the resulting *NSE* for all the 500 simulations. The sensitivity

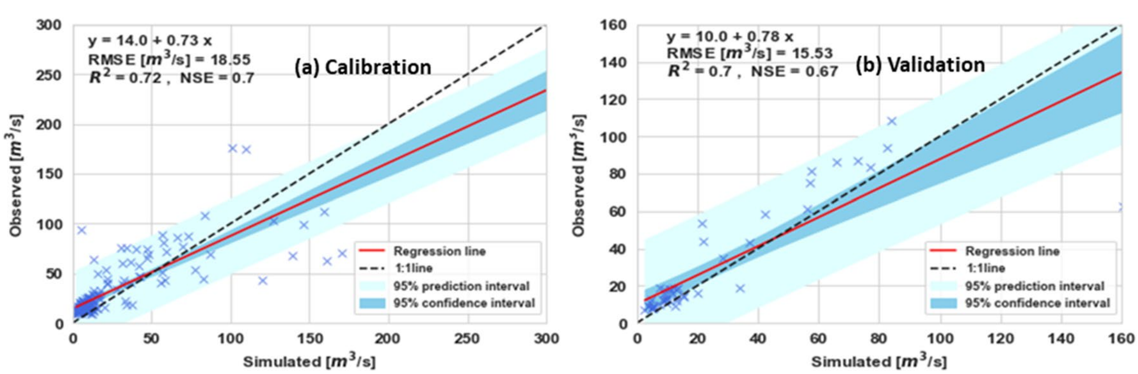

Fig. 5 Inter-comparison for observed and simulated daily stream flow for **a** calibration and **b** validation periods

Table 4 Performance evaluation of model for calibration and validation period

Statistical parameters	Calibration (2000–2010)	Validation (2011–2013)
Nash–Sutcliffe Efficiency (*NSE*)	0.7	0.67
Root mean squared error (*RMSE*) (m^3/s)	18.55	15.53
Coefficient of determination (R^2)	0.72	0.7

analysis of various parameters is a crucial step to see its influence on discharge in hydrological modelling. *P*-value is used for ranking of sensitive parameters. The *p*-value is used to determine the statistical significance of the sensitivity analyses. The significance level is denoted by the *p*-value, and the confidence level is denoted by $(1 - p)$. If the *p*-value is 0.05, for example, there is 95% confidence level that results are significant. Figure 7 shows the most sensitive parameters and their significance (as determined by the *p*-value). For future simulation, a hydrological model should be well calibrated. Since observed data is available for 2013, the validation is performed for 3 years, i.e., 2011–2013. It is evident from the graph that model-simulated value is well correlated with observed output in terms of temporal signature. Hence, the model is validated over the catchment for simulating discharge. The peak flows are well captured by SWAT simulation output. It can be envisaged from Fig. 5 that most of SWAT simulated streamflow was found to be concentrated along the 1:1 line, depicting an improved performance of the proposed model in modelling the streamflow from a Himalayan basin. The result found in this study is similar in line with observation reported by Haregeweyn and Yohannes (2003) and Swain et al. (2022). As a result, the model can be used to simulate discharge over the basin as well as to assess the effects of climate change on the catchment's hydrology. This study validates the value of high-resolution remote imaging. This research should be expanded to other mountainous catchments using cutting-edge geospatial inputs, which can aid in improving hydrological model performances and addressing water availability concerns in such areas.

Conclusion

In the present research study, widely used SWAT hydrological modelling is evaluated using high-resolution input (Sentinel, Sentinel 2 LULC, IMD gridded data) to check its applicability for Kosi river basin. The model was calibrated and validated using a SWAT-CUP package known as SUFI-2 for obtaining effective model predictions. A trade-off effect was evident between the SWAT model performance for the low and peak discharge. It was

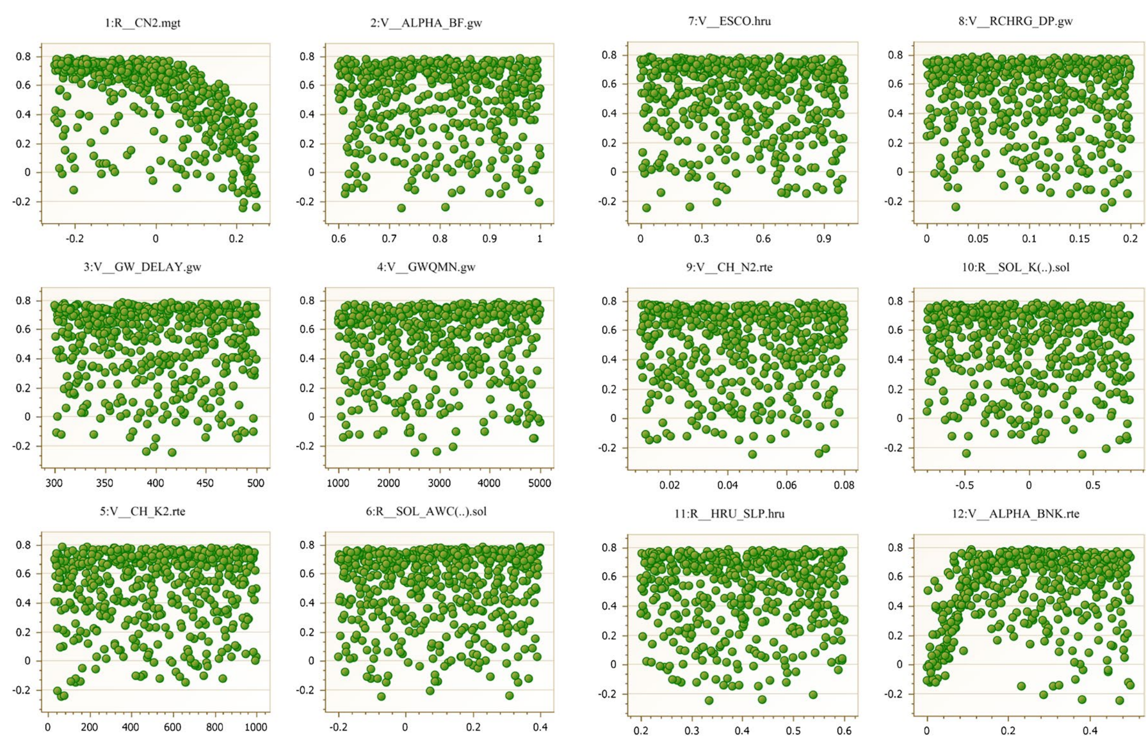

Fig. 6 Dotty plots of all the parameters considered for SWAT calibration (note: For each dotty plot, the *X*-axis represents the parameter's value for each simulation and the *Y*-axis represents the corresponding *NSE* values.)

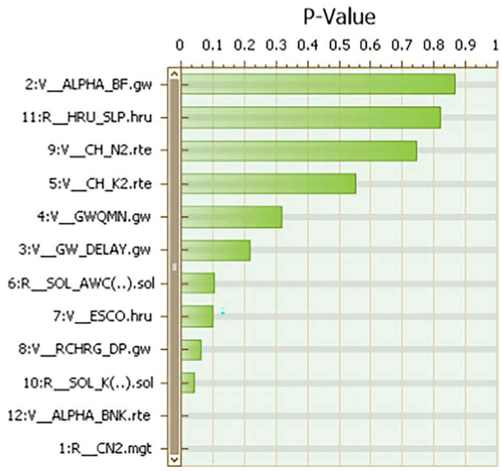

Fig. 7 Sensitivity chart (based on *p*-value) of the parameters considered for calibration of SWAT model

found that parameter related to topographical variation had higher sensitivity during calibration. For mountainous river basin, a very good hydrographic fit was obtained during model calibration. The result showed that there is reasonable match between observed and computed runoff as demonstrated on the basis of model performance indicators, which indicate that the model can be used to simulate runoff in Kosi river basin for practical use for planning purposes. The information reported in this study substantiates the utility of high-resolution remotely sensed information for hydrological modelling over the mountainous catchments in general and the Kosi river basin catchment in particular. This study can be utilized by water resource managers for the identification of key watershed problems and the formulation of effective management policies. Before applying watershed management options, the order of priority for each sub-basin needs to be taken into consideration for effective and economic utilization of funds.

Acknowledgements This work is carried out as Ph.D.'s thesis work at Division of Agricultural Engineering, ICAR-Indian Agricultural Research Institute, New Delhi. The authors thankfully acknowledge the Division of Agricultural Engineering, ICAR-Indian Agricultural Research Institute, New Delhi, and ICAR-Vivekananda Parvatiya Krishi Anusandhan Sansthan, Almora, Uttarakhand for providing necessary facilities during the course of investigation.

Funding ICAR-Vivekananda Parvatiya Krishi Anusandhan Sansthan, Almora, Uttarakhand, provided financial support.

Declarations

Conflict of interest The authors declare no competing interests.

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