SWAT Modeling to Assess Water Availability in the Command Area of the Gandak River Basin, India

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ABSTRACT

It is essential to analyze water availability in a sub-basin for the management of water resources. In this study, a sub-basin of the Gandak River, with an area of 973.54 km^2, has been selected to study water availability using a SWAT model with remote sensing and GIS support. For the analysis, hydrological and meteorological data for the year 2002 to 2021 have been used in addition to the land-use/land cover maps, soil map, and slope map. The SWAT model was simulated throughout a twenty-one-year period (from 2002 to 2021). To determine the most important watershed parameters, a sensitivity analysis of the model was carried out. Calibration was performed using data from 2002 to 2014 and validated from 2015 to 2021. The following statistical parameters were measured: Coefficient of determination (R^2), Root Mean Square Error (RMSE), Percent Bias (PBIAS), and Nash Sutcliffe Efficiency (NSE). The results obtained for these statistical parameters indicate that the model results are satisfactory.

1. INTRODUCTION

Biodiversity is negatively affected by increasing changes in water regimes, precipitation, and temperatures in numerous watercourses (Janjić and Tadić 2023). Water resources have a significant impact on human life, concerning the social, economic, migratory, food production, and health of ecosystems (Dube et al. 2022). Accurate estimations of the water balance's components, including runoff, evapotranspiration, infiltration, and groundwater flow, are required to achieve the necessary biodiversity in the basin. In fact, climate change and land use play big role in the assessment of water resources. Currently, environmental changes, biotic extinction, water, land, and air pollution are caused by changes in land use and land cover (Sultana et al. 2023). The water budget of river catchments is anticipated to be significantly impacted by land use change in addition to climate change (DeFries and Eshleman 2004). If land use change (LUC) is not properly managed, it may increase the detrimental effects of climate change on watershed hydrology (Labbe et al. 2023). LUC has a direct impact on the processes that generate runoff and modify the water resources in watersheds (Idrees et al. 2022). To

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address the water demand with an adequate amount of supply, one needs to have a proper understanding of water balance within the study area. Nowadays, together with the development of GIS, there are many hydrological models to help calculate the water discharge more accurately, easier, and faster than the traditional measurement methods. One of them is SWAT (Soil and Water Assessment Tool) (Nasiri et al. 2020). SWAT is a basin-scale model integrated with GIS technology which helps to improve the accuracy of simulated results of water discharge from rainfall and physical properties of the basin. The SWAT model is used in this study to assess a sub-basin of India's Gandak River. This model was selected for its extensive capabilities in simulating hydrological processes and water quality implications across wide and complicated watersheds. The model can integrate different land use practices, soil types, and climatic conditions, making it ideal for evaluating the effects of agricultural operations and conservation efforts in the Gandak River sub-basin. Hydrological catchment models must be used to estimate water fluxes in dynamic ecosystems with shifting boundary conditions. To be able to assess the changes brought on by environmental change, models should be validated for various environmental factors, such as various climatic situations, soils, geography, and vegetation cover (Chisadza et al. 2023).

The most crucial component of water resource development and management programs is understanding hydrological processes to create appropriate models for a watershed. The foundational and essential infrastructure for a country's sustained growth is the development of its water resources. Watershed scale modeling has become an essential tool for understanding complicated natural processes, assessing pollution loads, and creating sustainable agriculture management methods at the basin scale over the past 21 years due to the close ties between land and water activities. The spatial and temporal properties of terrain, soil, land use, climatic conditions, and precipitation can be effectively utilized by the distributed physically based hydrologic models for modeling hydrologic processes. Watershed modeling depends on a variety of variables, including scientific understanding of the hydrologic and water quality processes, management considerations, environmental considerations, and the accessibility of technology and data (Borah and Bera 2004). Hydrological models need sporadic meteorological data (precipitation, temperature, wind speed, etc.) which presents a large problem in poorly gauged places like semi-arid regions (Liu et al. 2022).

Based on the above information, the study was carried out for the assessment of water availability in a sub-basin of the Gandak River in India using SWAT model in the command area of 973.54 km^2. Despite significant advancements, there was no assessment of water availability in the command area of the Gandak River basin using a SWAT model. The study was done to fill gaps and investigate the region. SWAT is a suitable model to evaluate the effects of agricultural operations and conservation efforts in the Gandak River sub-basin of India.

2. Study area and data collection

2.1 Study area

The study area is a portion of the lower Gandak basin's alluvial plains, located between the latitudes of 25°30′25" and 26°45′00" N, and longitudes of 85°5′31" and 85°40′15" E. The study area is estimated to be 973.54 km^2 including part of the districts of Samastipur, Hajipur, and

Bhagwanpur, in Bihar. There are two rivers in the area, the Gandak and Burhi Gandak, which form the western and eastern boundaries, respectively (see Figure 1).

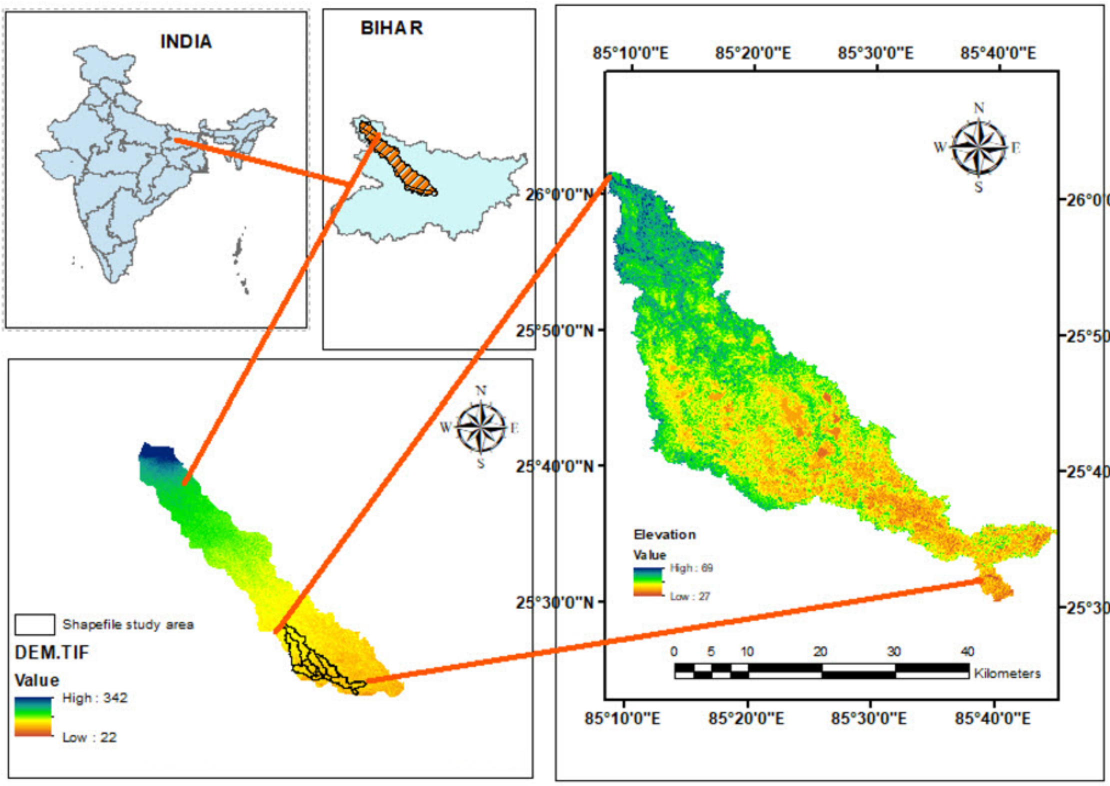


Figure 1 Location map of watershed area.

The maximum ground elevation is in the northwest and is 66.75 m above sea level; the minimum is in the southeast and is 39.12 m above sea level. The area has a slope that varies from 1 in 5,000, to 1 in 20,000 from NW to SE. Ten percent of the region's 1,168 mm of annual precipitation falls between March and June, 85% falls during July and October during Kharif, and the remaining 5% falls during November and February, during the Rabi period for planting. April to June are the warmest months in the region. The area's soil is highly productive and can hold onto moisture. This layer usually ranges from 15 to 20 m thick.

2.2 Data collection

The temperature, wind speed, relative humidity, solar radiation, precipitation, and maximum and minimum daily values data are available from 2002 to 2021 and were used for evaluation in the present study (Figure 2).

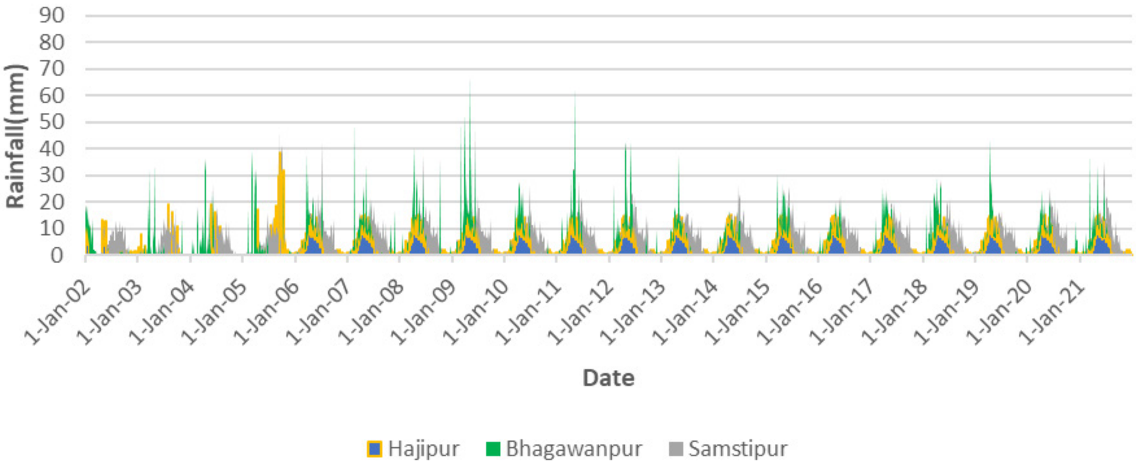


Figure 2 Time series plot of observed daily rainfall data.

The topography of the watershed was defined using a Digital Elevation Model (DEM). With a spatial resolution of 30 m, the SRTM DEM was downloaded from https://bhuvan.nrsc.gov.in/home/index.php. The Indian Space Research Organization (ISRO) created the Cartosat-1 Digital Elevation Model (CartoDEM), a national DEM. The Cartosat-1 stereo payload, which was launched in May 2005, served as its model. Most watershed characteristics, including watershed boundary (catchment area), watershed drainage patterns, aspect, slope, and length of sloping terrain, were acquired using the DEM. The DEM data can also be used to determine drainage properties, including channel slope, length, and width (Dhami et al. 2018).

Land use (Figure 3) was mapped from the 2021 Landsat-8 image at a spatial resolution of 30 m, downloaded from the USGS website (http://earthexplorer.usgs.gov/). The supervised image classification “maximum likelihood” method was used to classify land use maps (Patel et al. 2019; Ara et al. 2023) for the study area using Landsat imagery. In our study area, the sub-basin area was divided into five land use classifications based on their percentage coverage: wetland (21.62%), agriculture land (11.89%), barren land (36.81%), and water (29.68%). Less than one-third of a geographical area is covered in vegetation, which is known as barren land, and the soil is typically sandy and dry. Water estimation depends on the scope and resolution of the remote sensing investigation, which can be applied to several different tasks, such as studies of runoff and precipitation. In the study area, a total of 29.68% of the area is covered by water bodies.

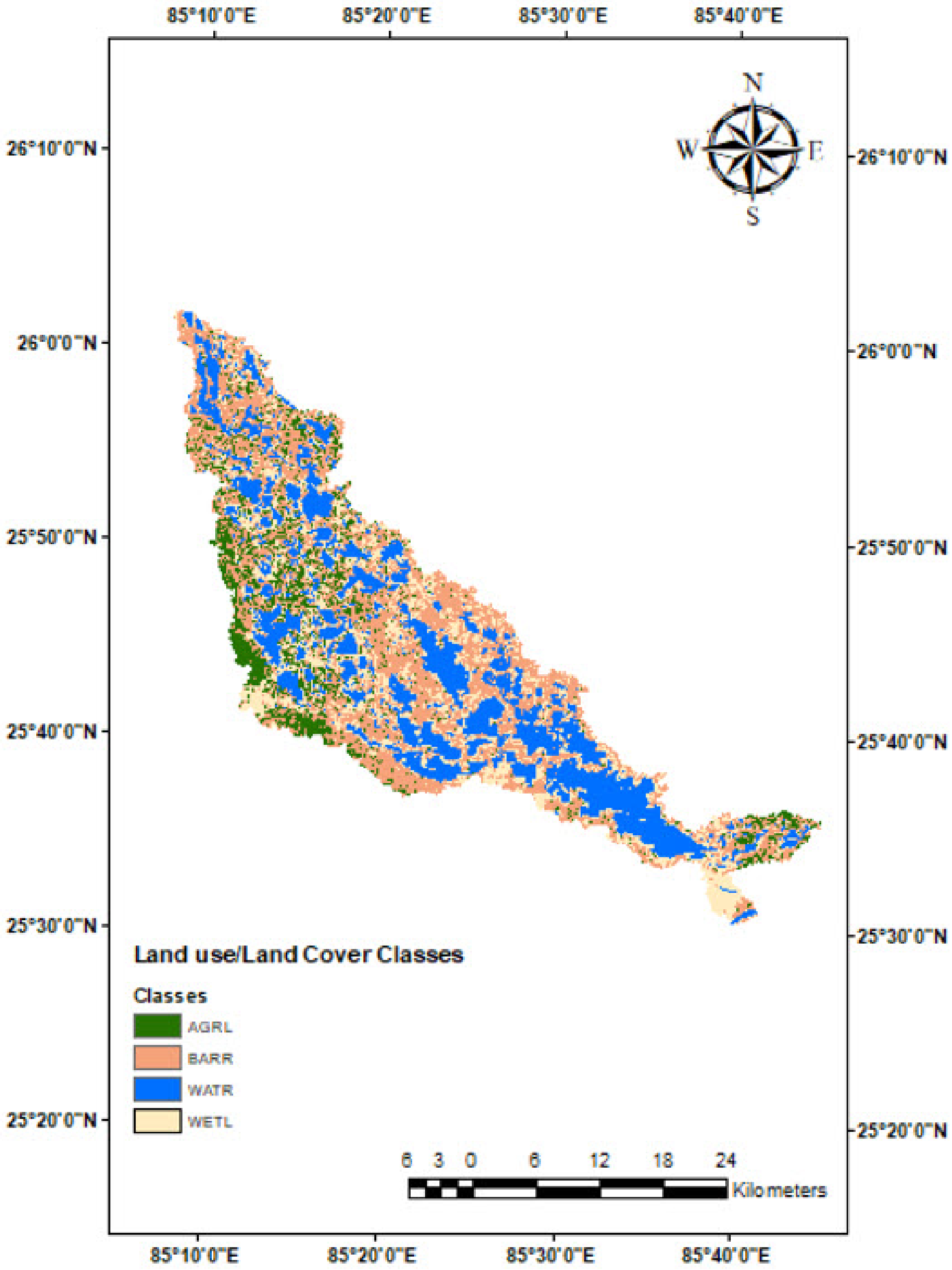


Figure 3 Study area land use map.

The soil map of the study area was found from Harmonized World Soil Database (HWSD) produced by the Agriculture and Food Organization of the United Nations (https://gaez.fao.org/pages/hwsd) (Figure 4). The sub-basin has 3 different FAO soil classes (Table 1 and Figure 4).

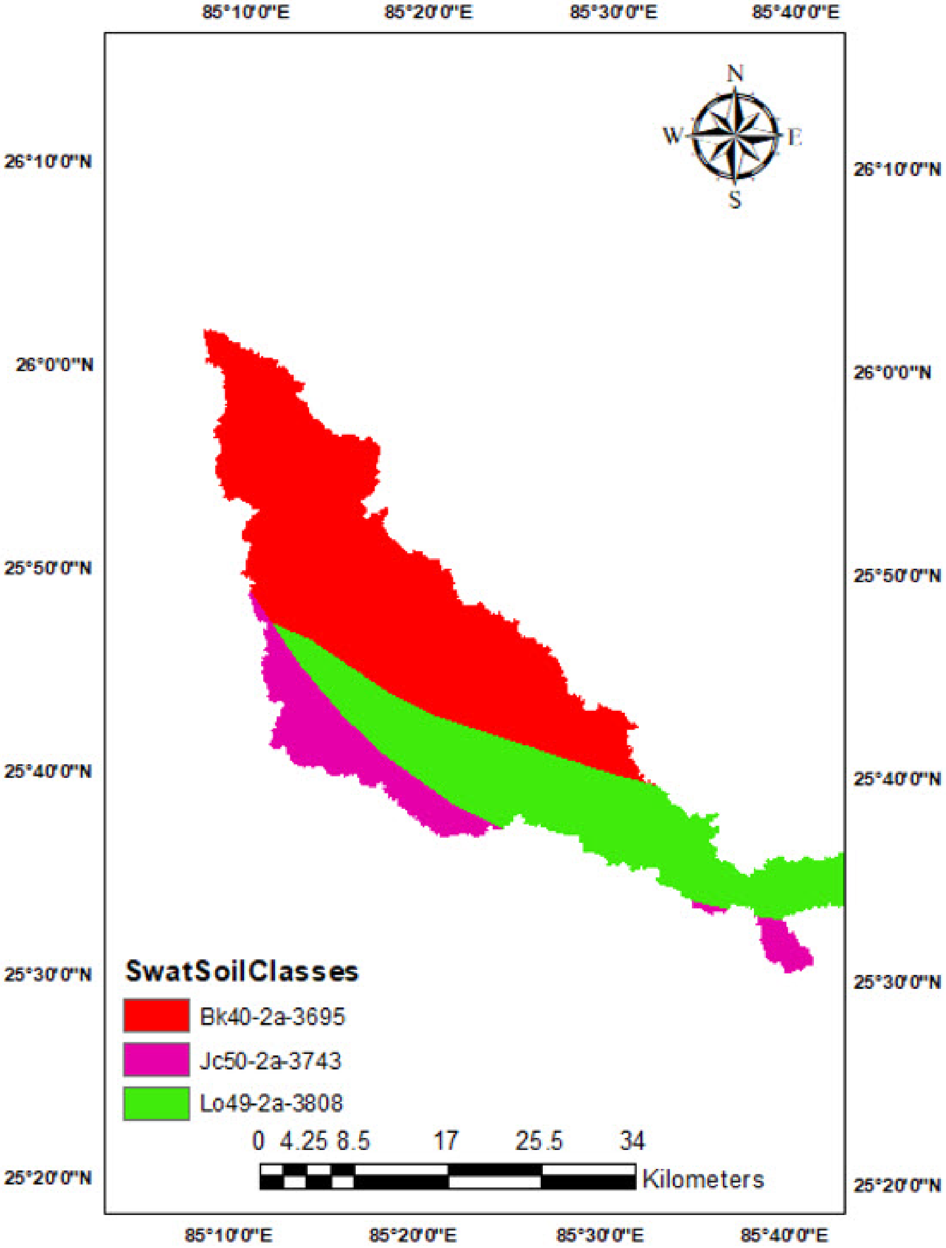


Figure 4 Soil map of the study area.

Table 1 Soil classes and percentage of sub-basin area covered.

Soil type (FAO soil codes)	% Sub-basin area
Bk40-2a-3695	54.69
Jc50-2a-3743	12.32
Lo49-2a-3808	32.99

3. METHODOLOGY

The SWAT model's water balance is used to calculate inflows and runoff as part of the process for assessing water availability. To determine an unknown component of the water balance, the water balance can be calculated for any hydrological cycle subsystem, regardless of its size and structure. The basic continuity equation for a system's water balance can be seen in Equation 1.

$$[\text{Input to the system}] - [\text{Outflow from the system}] = [\text{Change in Storage}] \qquad (1)$$

3.1 Hydrologic simulator (SWAT model)

For the watershed, a distributed hydrologic model known as AVSWAT (the SWAT extension of ArcView GIS) was applied. The SWAT system is a continuous model that is process-based, spatially scattered, and time-based. It was developed by the USDA Agriculture Research Service (ARS) (Wang et al. 2019). Many watershed hydrologists utilize the SWAT model to analyze how agricultural practices and land use supervision affect the overall health of the watershed, as well as streamflow and water quality. Researchers have determined that the SWAT model predicts with a high degree of efficiency, and it has a reliability that has been validated in numerous locations all over the world. The most recent version is SWAT 2012, which can be found at https://swat.tamu.edu/. Open-source SWAT model software is widely accessible online. The SWAT platform is designed to forecast how land use and land cover will affect sediment, water, and agricultural chemical yields in watersheds that have not yet been registered. It works with a daily time step. The ArcSWAT model divides a watershed into numerous interconnected sub-basins (Adnan et al. 2019). Each sub-basin is further divided into various Hydrological Response Units (HRUs) based on the type of land use, slope, and soil. Prior to integrating at the sub-basin scale, the water level is first calculated at the HRU scale. Specific climatic input factors, such as temperature, solar radiation, precipitation, relative humidity, and wind speed are necessary for the model to achieve this goal. For model setup, additional data beyond the climatic parameters is needed, including a topographical map or DEM, soil characteristics, land management and vegetation, and methods present in the watershed (Santhi et al. 2006). The soil map, land use/cover map, and digital elevation model were all projected into a single projection system to set up the model. The model provides the capacity to partition the DEM into watersheds, basins, and sub-basins. Hydrological response units (HRUs) were created by superimposing the categories of land use/land cover, soil, map, and slopes. According to Arnold et al. (2012), "hydrologic response units" (HRUs) are the distinct confluence of slope, soil, and land use features. SWAT is a physically based tool, rather than statistically based, and was used as the model in this investigation (Arnold et al. 2012). This enabled greater dependability and improved performance, which was crucial for a study of this size, and is particularly important in basins without gauging stations. The water budget can be determined using this model (Boufala et al. 2019). The SWAT model can reproduce hydrological processes with a respectable level of accuracy, according to an evaluation of its application to Ethiopian circumstances at comparatively bigger watersheds. SWAT simulates the hydrological cycle using the water balance equation for the land phase of the cycle in Equation 2.

$$SW_t - SW_o = \Sigma_{i=1}^{t}\left(R_{day} - Q_{surf} - E_T - W_{inf} - W_{rf}\right) \qquad (2)$$

Where:

SW_t = soil water content at time t,
SW_o = initial soil water content (at time $t = 0$),
t = time in days,
R_{day} = daily precipitation amount (mm),
Q_{surf} = amount of surface streamflow on a day mm),
E_T = amount of evapotranspiration on a day (mm),
W_{inf} = amount of infiltration on a day (mm), and
W_{rf} = return flow (mm).

The model uses the SCS curve number (CN) to calculate the surface runoff. The relationship between runoff, rainfall, and retention parameters is expressed in Equation 3, whereas the correlation between the retention parameters and curve number (CN) is expressed in Equation 4.

$$Q_{surf} = \frac{\left(R_{day} - 0.2S\right)^2}{\left(R_{day} + 0.8S\right)} \tag{3}$$

$$S = 25.4\left[\frac{100}{CN} - 10\right] \tag{4}$$

Where:

S = Maximum potential retention after runoff begins (mm) (*depends on land use, soil type, and antecedent moisture conditions*), and
CN = curve number.

Depending on the availability of the input data, the catchment's potential evapotranspiration (PET) could be modeled using the Penman-Monteith approach (Dash et al. 2021; Monteith 1965), or the Priestley-Taylor approach (Priestley and Taylor 1972); this study used the Penman-Monteith approach to compute the PET. The modified universal soil loss equation (MUSLE), invented by Wischmeier and Smith (1978) and Rodríguez-Blanco et al. (2016), is used in SWAT to estimate the catchment-scale sediment output.

3.2 Watershed delineation

A digital elevation model (DEM) was generated using ArcGIS to generate the watershed's stream network and identify the outlet locations for a particular threshold value. The main watershed was divided into nine sub-watersheds by automatic delineation (Figure 5). The area covered by the sub-basin is shown in Table 2.

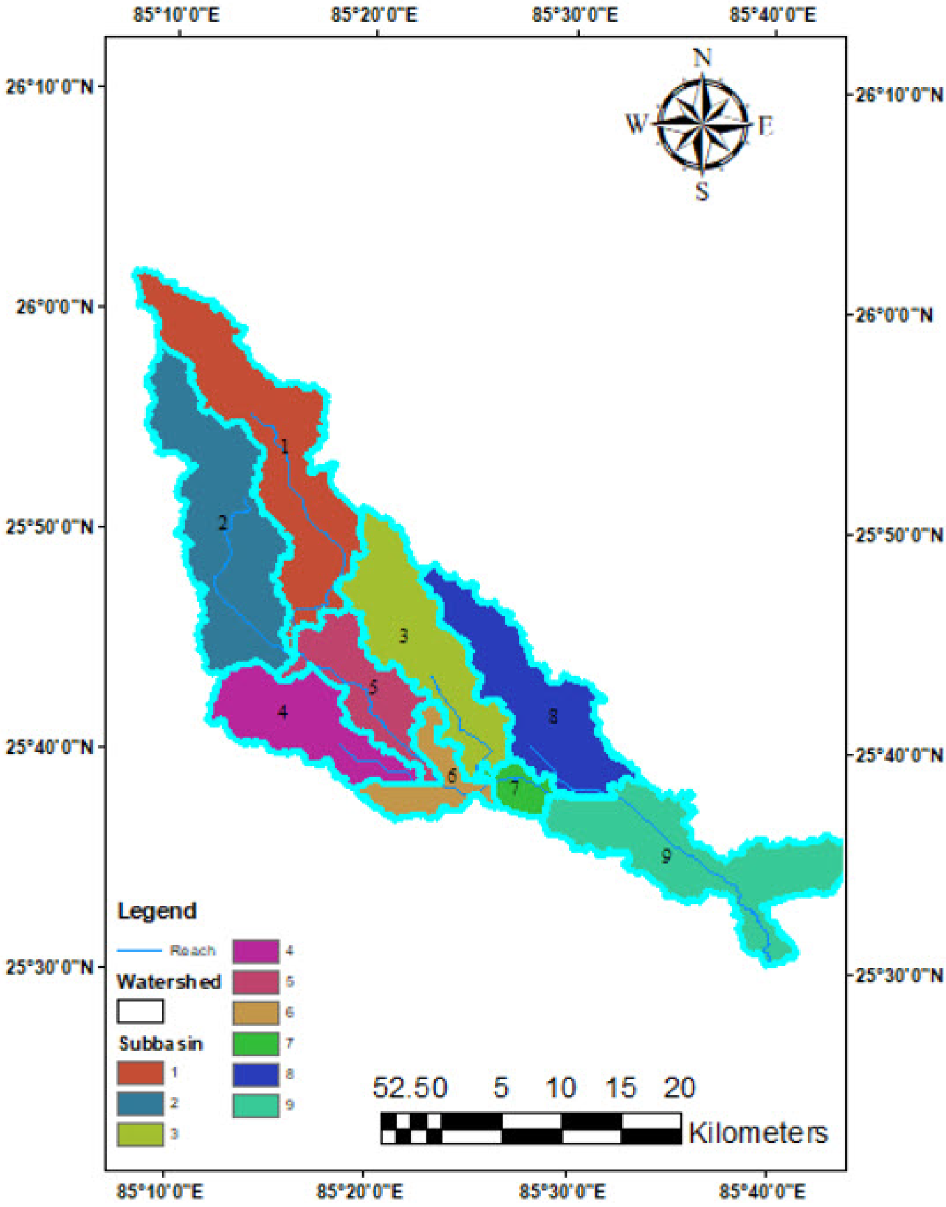


Figure 5 Sub-basin and outlet point.

Table 2 Sub-basin area.

Sub-basin	Area (km^2)
1	185.204
2	173.278
3	122.850
4	90.720
5	72.466
6	41.504
7	19.292
8	121.213
9	147.003
Total	973.528

3.3 Formulation of database

For this research, the ArcSWAT graphical user interface was utilized to operate and carry out the key SWAT model functions from the ArcGIS tool. The first stage in applying the SWAT model is to define the examined watershed and then split it into numerous sub-basins based on the outlets produced by the junction of reaches or those determined using a digital elevation model (DEM). After that, each sub-basin is separated into uniform regions known as hydrologic response units (HRUs), which GIS produces from the overlaying of slope, land use, and soil layers. In the ArcSWAT interface, the four main types of spatial data are DEMs, soil types, slopes, and land use, which are shown in an overview of the methodology (Figure 6).

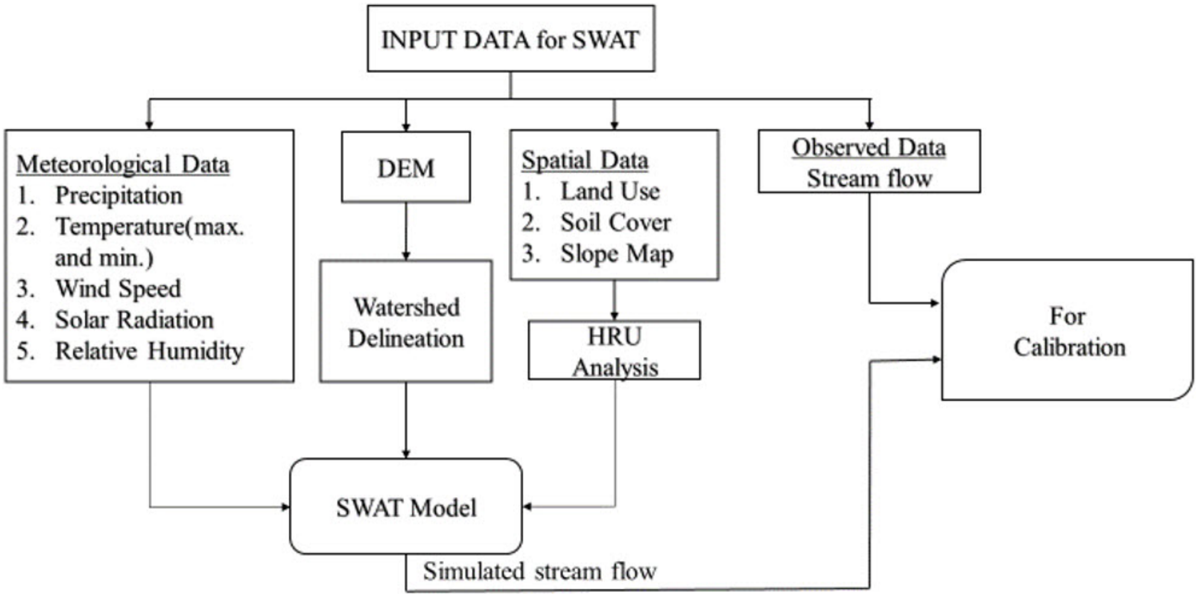
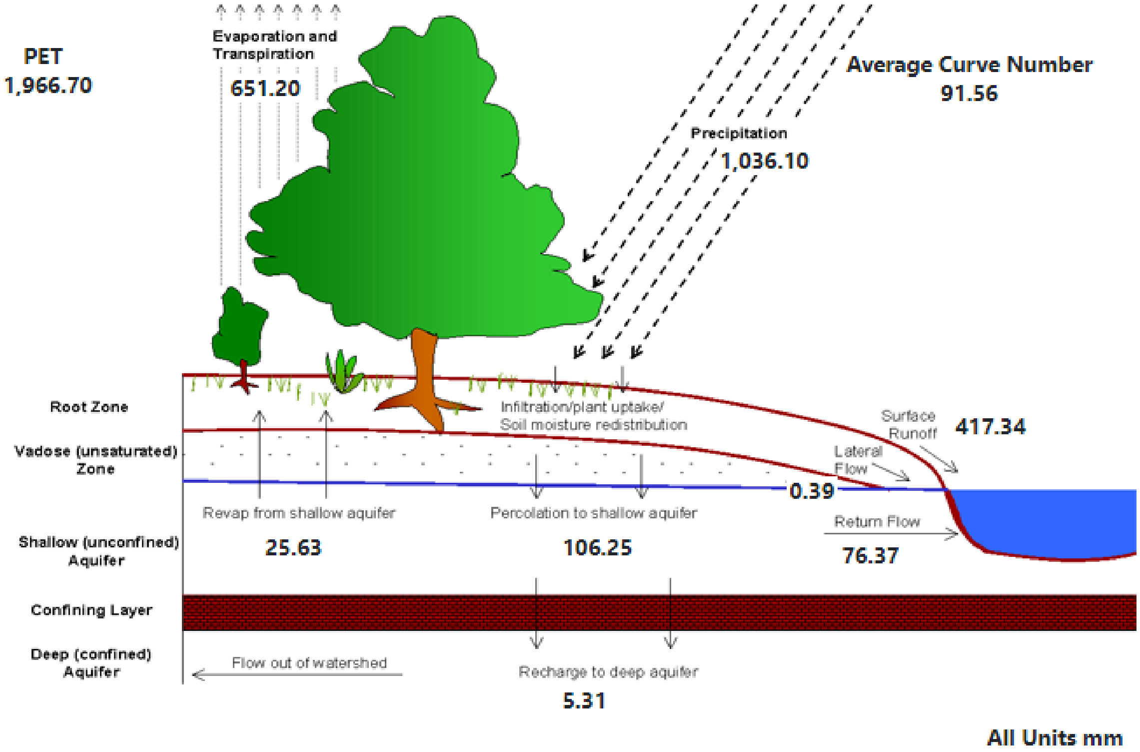


Figure 6 Overview of the methodology.

4. RESULTS AND DISCUSSION

4.1 Hydrological variable estimation

Figure 7 illustrates the hydrology cycle of the pilot area of a sub-basin of Gandak River using a SWAT model (from 2002 to 2021). The results show that the average annual precipitation is 1,036.10 mm, the average annual evapotranspiration (ET) is 651.20 mm, the average annual PET (potential evapotranspiration) is 1,966.70 mm, the average annual surface runoff is 417.33 mm, the average annual lateral flow is 0.39 mm, and the average annual percolation to shallow aquifer is 106.25 mm. Figure 8 and Table 3 represent the average monthly sub-basin values of precipitation, water yield, and actual evapotranspiration obtained using the SWAT model. It shows that rainfall increased from May to July and decreased from August to December. Similarly, evapotranspiration and potential evapotranspiration are also higher during this period. Table 3 shows the average annual monthly hydrological variables in the study area.



Stream Flow/Precipitation	0.48
Surface Runoff/Total Flow	0.84
Base Runoff/Total Flow	0.16
Percolation/Precipitation	0.10
Deep recharge/Precipitation	0.01
ET/Precipitation	0.63

Figure 7 Visual SWAT output, sub-basin of Gandak River.

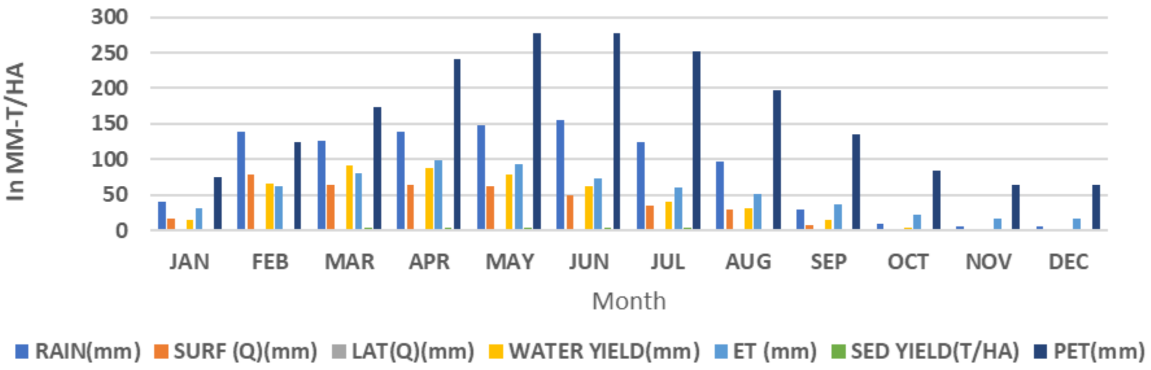


Figure 8 Average monthly sub-basin values of precipitation, water yield, and actual evapotranspiration obtained using SWAT model.

Table 3 Average annual monthly hydrological variables in the study area.

Month	Rainfall (mm)	Surface runoff (mm)	Lateral flow Q (mm)	Water yield (mm)	ET (mm)	Sediment yield (T/HA)	PET (mm)
Jan	20.98	6.02	0.01	6.00	22.43	0.16	63.26
Feb	40.84	16.75	0.02	14.63	31.16	0.42	75.89
March	138.55	78.12	0.03	65.30	62.01	2.74	124.10
Apr	126.89	64.27	0.05	90.93	81.33	3.34	172.59
May	139.02	64.05	0.06	87.71	98.57	3.13	241.64
June	148.81	62.55	0.05	78.70	93.22	3.44	277.27
July	155.03	49.73	0.05	61.86	73.06	4.63	277.07
Aug	123.73	35.52	0.04	40.30	61.28	3.41	251.68
Sep	97.20	29.04	0.03	31.61	51.88	2.53	197.94
Oct	28.85	7.79	0.02	15.52	36.47	0.66	134.95
Nov	9.63	2.31	0.02	3.75	22.19	0.05	84.10
Dec	5.43	0.72	0.01	2.60	17.01	0.03	64.56

NOTE: ET–Evapotranspiration, PET–Potential evapotranspiration.

4.2 Analysis of flow in the study region

Model simulation

The model is prepared for simulation once all inputs have been finalized, and data files have been generated. The simulation is performed for 21 years, from 2002–2021. See Figure 9 for the time series plot of observed versus simulated daily discharge during the monsoon period (2002–2021) pilot area of a sub-basin of the Gandak River.

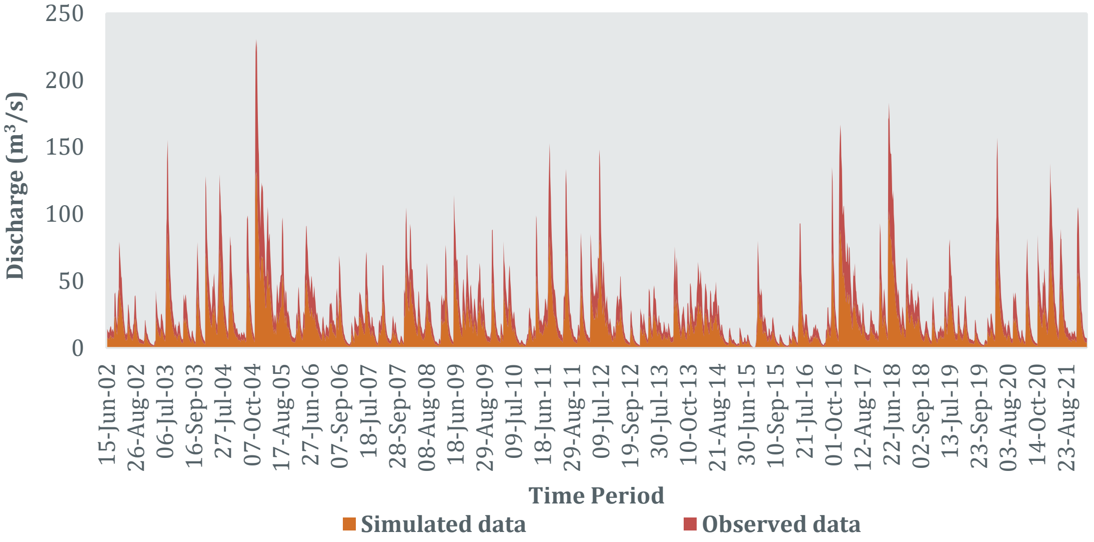


Figure 9 Time series plot of observed versus simulated daily discharge of monsoon period (2002–2021).

Model efficiency

The correctness of the results obtained by the model can be assessed and evaluated using a variety of techniques. Using the Coefficient of Determination (R^2) and three commonly used statistic coefficients—percent bias (PBIAS), RMSE, and Nash-Sutcliffe efficiency index (NSE), observations for the calibration and validation were completed.

Coefficient of Determination (R^2)

Using the Coefficient of Determination is an excellent approach to highlight the consistency between simulated and observed data. Higher values indicate reduced error variation, and values larger than 0.50 are regarded as satisfactory (Santhi et al. 2001; Nasiri et al. 2020). It goes from zero to 1.0. See Figures 10(a) and 10(b) for river discharge scatter plots for daily stream flow:

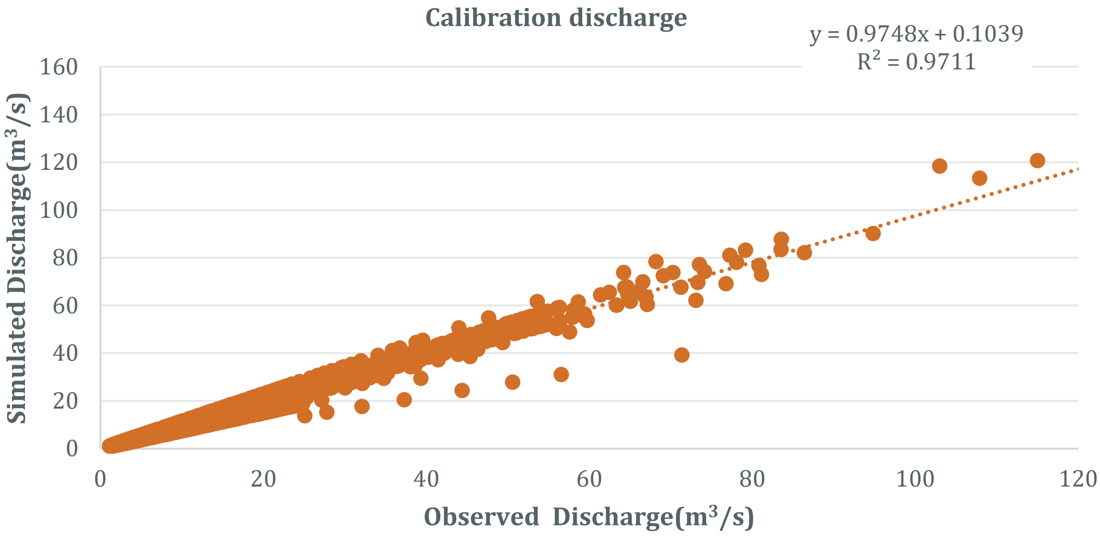


Figure 10(a) Calibration of the model by river discharge scatter plots for daily stream flow.

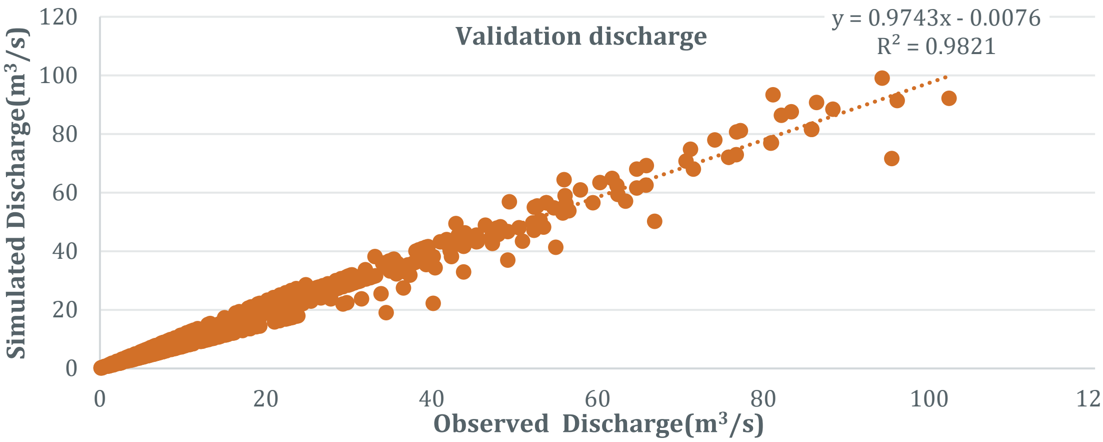


Figure 10(b) Validation of the model by river discharge scatter plots for daily stream flow.

Calibration results

The SWAT model was calibrated for the inflow data for the years 2002–2014 after it ran with good precision and sensitive parameters were identified. These optimal simulated flow values demonstrate the model's accuracy and performance. After achieving the results, it was evident that there was a satisfactory match between the calibrated model's observed and simulated values. Table 4 shows the parameters used in the SWAT model for calibration. According to Gupta et al. (1999), the best value of PBIAS is zero. This means that lower PBIAS values suggest a more accurate simulation of the model. The model's accuracy is indicated by the following parameters.

Table 4 Calibration parameters used in SWAT model.

R^2	RMSE	PBIAS (%)	NSE
0.97	2.775	-1.957	0.9862

Validation results

The period from 2015–2021 is used for validating the results. Along with the daily simulated data time series graphic, there is a comparison between the simulated and observed flow. Table 5 shows the parameters used for validation in the SWAT model. The model's accuracy is indicated by the following parameters.

Table 5 Validation parameters used in SWAT model.

R^2	RMSE	PBIAS (%)	NSE
0.98	2.340	-2.685	0.9901

5. CONCLUSION

The most crucial part of managing water resources is developing an appropriate model for the hydrological process in a river basin. The assessment of water quantity and quality is likely to be done using hydrologic simulation models that are based on watersheds. The SWAT model successfully performed and was applicable to this study. To comprehend the primary reason for the limitation on water sharing, one must be aware of the micro-level availability of water. The application of the SWAT model to water balancing and annual, lean season surface water simulation was the primary emphasis of this work. It is especially useful in situations when there is a lack of water flow data. The study suggests that the SWAT model could be a promising tool to predict water balance and water yield to support policies and decision-making for sustainable water management at the sub- basin level. Therefore, understanding the water balance will be useful for studies on the operational management of reservoirs and river sub-basins. Using four popular statistical parameters such as the Root Mean Square Error (RMSE), Coefficient of Determination (R^2), PBIAS, and the Nash and Sutcliffe Efficiency (NSE), for calibration: ($R^2 = 0.97$), (RMSE = 2.775), (PBIAS (%) = -1.957), and (NSE = 0.9862), and for validation: ($R^2 = 0.98$), (RMSE = 2.340), (PBIAS (%) = -2.685), and (NSE = 0.9901). These results indicate that the model shows good and acceptable performance.

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