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Hydrological Modeling of Bhagirathi River Basin Up to Tehri Dam Using ArcSWAT

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Abstract

The river Bhagirathi comes from Gaumukh Glacier and merges with Alaknanda before flowing for about 193km to form River Ganga at Devprayag. Due to the intensity of the flooding in this area, the Bhagirathi watershed basin, one of the most significant basins in Northern India, necessitates aggressive water resource management. There are no significant studies available for Bhagirathi basin of northern India. The study is an attempt to utilize the Soil and Water Assessment Tool to simulate streamflow in this basin via a watershed model called ArcSWAT. The outcomes of this study will be helpful in water resource management and mitigation of flood in this basin. This study includes Sequential Uncertainty Fitting technique, which was applied for analysis of the data and allowed for calibration and global sensitivity using the SWAT-Calibration and Uncertainty Program (SWAT-CUP). The feasibility of this model was reported on the basis of R^2 and NSE (Nash Sutcliffe efficiency**)**. Together, these variables show how well the SWAT model's calibration-uncertainty analysis has been done. After the calibration and validation, a global sensitivity analysis was conducted to identify the parameters in the basin that were the most sensitive. Results shows the GW_DELAY (Ground Water Delay) was found most sensitive parameter. The results of this study can be utilised efficaciously in the Bhagirathi basin to mitigate floods, manage droughts, water resource management, and prepare for hydraulic structures, according to the statistical parameters of this study.

Keywords

Hydrological modelling, calibration, validation, watershed

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1. Introduction

One of the most important natural resources is water; because entire life system depends on it. Water resources on earth cannot be altered, but it can be regulated. The impacts and distribution of water issues may be minimized by handling supplies in two ways: by increasing the available supply and reducing the excessive demands and eliminating the losses. But this control isn't as simple as it seems and involves numerous factors together with environment (temperature, precipitation), population, settlements, use, economic factors and much more. From a hydrological viewpoint, the various stages of the hydrological cycle in the river basin/watershed depend on the various natural factors and human influences.

Most of the ancient civilizations were often found along the river side, demonstrating the value of water as a tool for domestic necessities including food production, transportation, and recreation. Some of these historical locations also saw significant human habitation over time, developing into megacities and modern communities. Many water issues are now plaguing these cities as a result of the significant population movement to these towns. Depending on its climatic, topographical, geological, and socioeconomic circumstances, each place has unique challenges with water quality and quantity. The potential impacts of climate change and global warming on weather patterns worldwide are significant. Studies conducted on modeling projections for the 2050s have suggested that the global freshwater flow may undergo a fundamental transformation [1] [2] [3]. Both surface water and groundwater are essential sources of water storage, but their overuse has resulted in resource depletion. Meeting the demand for high-quality water while ensuring a balance between supply and demand is a major challenge nowadays. If there are no measures taken to stop the overuse of the resource, the growing demand for water could have a significant impact on future supply [4] [5]. In order to preserve the ideal balance of sustainable advantages for current generations and societies, water resource management is crucial for integrating all environmental, economic and social problems within the river basin [6].

To efficiently manage water resources in the river basin, it is crucial to have an understanding of the hydrological cycle. This cycle describes how water moves between the hydrosphere, biosphere, atmosphere, and lithosphere. Processes like condensation, evaporation, rainfall, absorption, drainage, sublimation, transpiration, melting, infiltration, and groundwater movement all play a role in carry water from one source to another [7]. Around 91% of the water that evaporates from the oceans returns through precipitation, with the remaining 9% falling on landmasses due to climatic situations [8]. India has 16% of the world's population and occupies around 2% of the planet's surface area, yet it only possesses 4% of the world's total water supply. India has a total surface water availability of 2309 and 1902 m^3 per person in 1991 and 2001, respectively [9]. However, it has been predicted that between the years 2025 and 2050, the amount of surface water available per person would likely decrease much more, to 1401 m^3 and 1140 m^3, respectively. The per capita availability of water in 2010 was 1545 m^3 when compared to the 6042 m^3 available in 1951 [10] [6].

1.1 Need of the Study

Besides being a hydrological unit, a river basin or watershed is also a socio-political-ecological unit that plays a critical role in determining rural citizens' health, social, and economic well-being [11]. Bhagirathi basin is one of the most significant river basins of northern India. It directly affects 5 states of the northern India. There are no significant studies and data available of this river basin. Therefore, Bhagirathi basin was selected for this study. This paper aims to provide a SWAT model which will contribute in mitigation of flood and water resource management in this river basin [12] [13] [6]. For the parameter analysis and calibration watershed was divided into small units. The impacts of natural climate variability, anthropogenic climate change, and human activities on the underlying surface on the hydrology of a basin were then discussed through basin hydrological simulation and future runoff prediction.

2. Material and methods

2.1 The Description of the study area

Gaumukh Glacier is the source of the Bhagirathi River, which joins the Alaknanda River near Devprayag in Garhwal and becomes the Ganges. It is 205 kilometers long and located in Uttarakhand. Before entering the Alaknanda at Devprayag, it travels 193 kilometers. The basin is located between latitudes 30° 43' and 31° 47' north and longitudes 78° 28' to 78° 98' east. The watershed covers 2514.254 km^2 in total. The Gangotri Glacier and the Khatling Glacier in the Garhwal, Himalaya, at an altitude of 3892 meters above mean sea level, are the sources of the Bhagirathi River's headwaters. Jadh Ganga at Bhaironghati, Kedar Ganga at Gangotri Siyan Gad near Jhala, Asi Ganga near Uttarkashi, Kakora Gad and Jalandhari Gad near Harshil, and Bhilangna River close to Old Tehri are some of the tributaries that enter the Bhagirathi River. The basin is located on the Himalayan Mountain range's southern flank. While the southern portion of the basin is heavily wooded and ranges in height from 3700m to 4100m, The Greater Himalayan mountains, also known as Himadri, which is covered with high Himalayan peaks and glaciers, make up part of the basin's northern region. At 3892 m is the elevation of the region where Bhagirathi rises.

2.2 Description of SWAT model

The SWAT model, a physically based, semi-distributed catchment (river basin) model that simulates evapotranspiration, plant growth, infiltration, percolation, runoff and nutrient loads, and erosion, was developed to assess the effects of land management methods on surface waters. This model is skilled at performing simulations indefinitely. The SWAT model distinguishes between two distinct phases of catchment processes [14] [12]. The first phase, known as the land phase, focuses on the transportation of water, sediment, nutrients, and pesticides from all sub basins to a major channel [15] [16] [17] [18] [19]. The second phase, known as the water routing phase, is concerned with processes that occur in the main channel leading to the catchment outlet [20]. A "catchment" under SWAT is further subdivided into "hydrologic response units" and "sub-basins" (HRUs). HRU are special assemblages of slope, soil, and land use. In the current study, modelling was done using SWAT 2012 [21] [22]. SWAT has two ways for figuring the surface runoff: the Green-Ampt infiltration method and the Modified SCS curve number (CN). In this work, the surface runoff volume was estimated using the SCS-CN approach. SWAT primarily uses the Priestley-Taylor, Penman-Monteith (PM), and Hargreaves methods to determine potential evapotranspiration. For determining evapotranspiration, we applied the Hargreaves approach the kinematic storage model was utilized to simulate lateral flow, while return flow was estimated by creating a shallow aquifer [23]. The hydrological balance is governed by the water balance equation, which is expressed as [24] [20].

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

Where:

- The final water content of the soil on day i (SWt) is measured in mm
- The initial water content of the soil on the same day (SW0) is also measured in mm
- The amount of rainfall on day i (Rday) is measured in mm
- Q_{surf} is the amount of surface runoff on day i (mm)
- The amount of evapotranspiration on day i (Ea) is also measured in mm
- W_{seep} is the volume of water entering the vadose zone from the soil profile on day i (mm)
- Q_{gw} represents the return flow on day i (mm)

The following equation describes the SCS curve number:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}$$

Where:

- Q represents the runoff depth in (mm)
- P represents effective precipitation in (mm)
- I_a represents the initial abstraction of water in (mm),
- S represents maximum potential retention.
- Initial abstraction of water I_a is the function of maximum potential retention S.

Therefore,
$I_a = \lambda S$
Where:
$\lambda=0.2$. Therefore, $I_a = 0.2 S$
By integrating both Equations we have;

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

When P is more than 0.5 S, runoff processes occur. Due to the influence of catchment slope, soil type, and land use management, the potential retention parameter exhibits variability. The following equation correlates the dimensionless parameter CN with potential maximum retention of S.

$$S = 25.4\left(\frac{1000}{CN} - 10\right)$$

The SCS curve number (CN) is impacted by various factors such as soil permeability, land use, infiltration, and soil water conditions (CN). It is possible to determine the CN value using three conditions: dry, average moist, and wet. The SWAT model has been developed and validated to generate several outputs, including evapotranspiration, surface runoff, stream flow, interception storage, deep aquifer, infiltration, and reservoir water balance.

2.3 Methodology and Swat Input

The SWAT model necessitates four primary types of data, including a digital elevation model (DEM) of the study area, information on land use and land cover, soil data, and a database of weather and hydrology. All of these data are utilized to develop the SWAT model. After the SWAT model was successfully used, SWAT-CUP was used to calibrate and validate the model.

2.4 Input Data

The stage of data collection is regarded as crucial in hydrological modeling because of the substantial amount of data needed. The selection of the study area was based on data availability to guarantee that adequate information was obtainable for the modeling process.

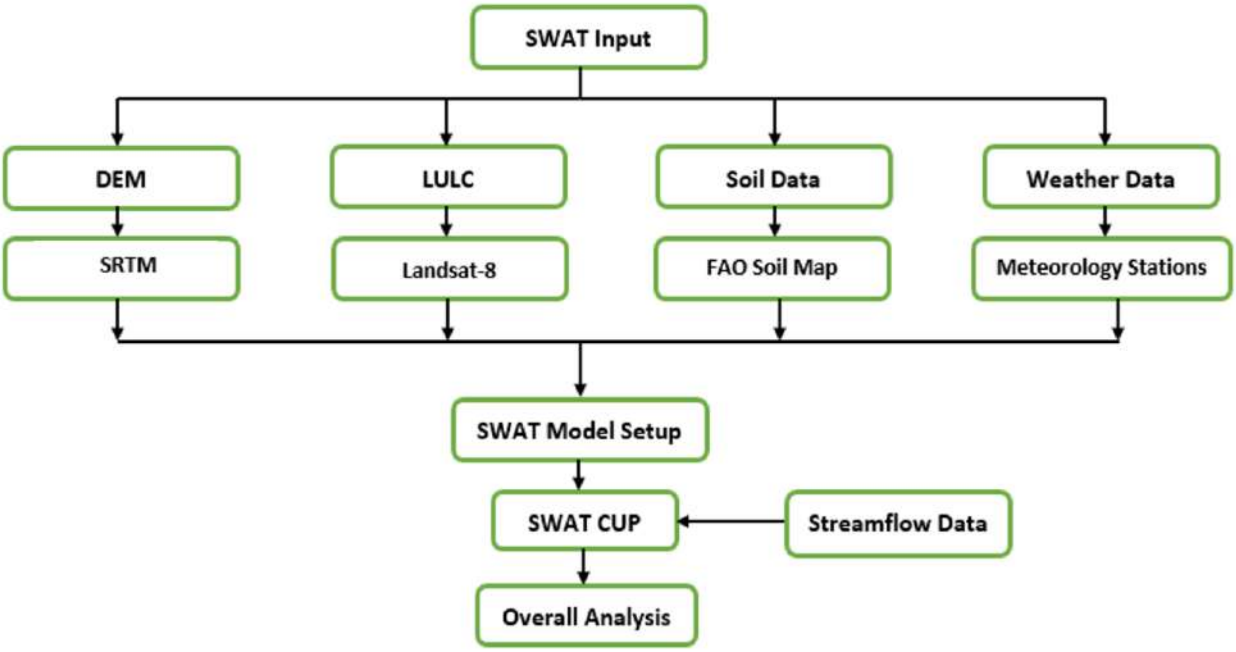


Fig. 1. Project Methodology

2.4.1 Digital Elevation Model (DEM)

A digital elevation model (DEM) is a raster dataset that comprises an array of cells or pixels that contain information about the elevation. To define the topography of the basin, a DEM was used to determine the elevation of each point in a given area at a specific spatial resolution Figure 2 shows the 90 m x 90 m resolution DEM that was obtained for the current investigation from the SRTM (Shuttle Radar Topography Mission). To create the necessary basin DEM, ArcGIS is used to process it and project it to the coordinate system (WGS 1984 UTM Zone 43 N). The stream streams, sub-basins, and other features like the slope map for HRUs are often delineated using DEM.

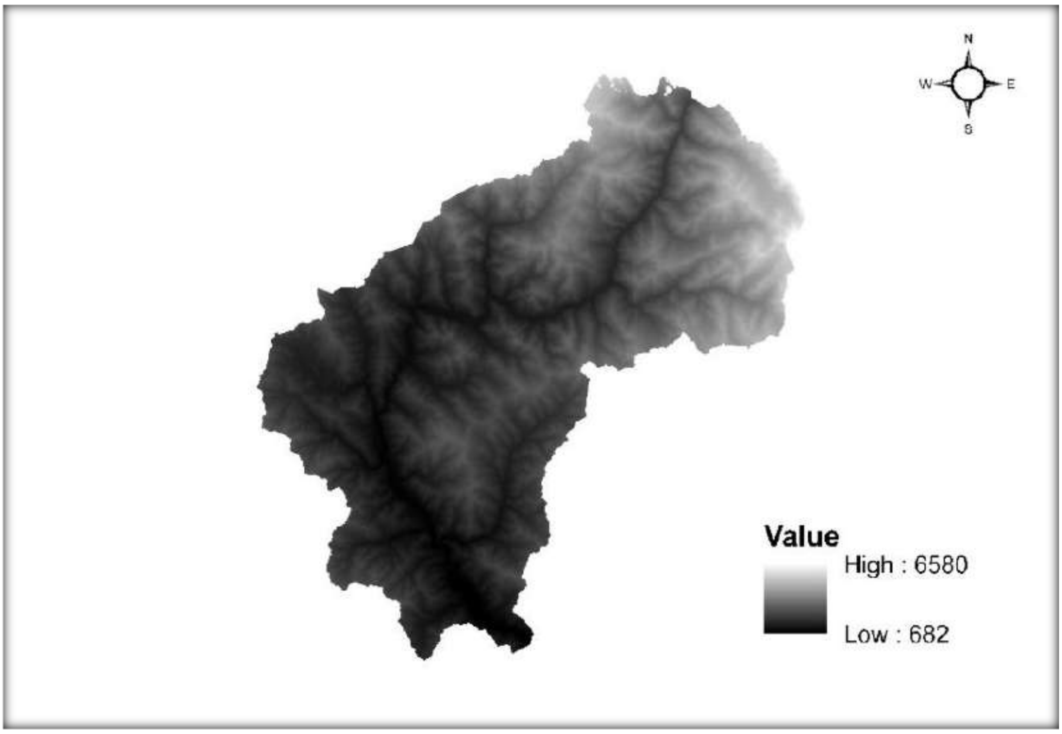


Fig. 2. Digital Elevation Model of Study Area

2.4.2 Land use/land cover (LULC)

Two of the most significant factors affecting runoff, surface erosion, and evapotranspiration in a watershed area are land use and land cover. ArcMap, which has a spatial resolution of 30 meters, is used to process Landsat 8 photographs 2020 to create the Land use land cover map. To reclassify the area's land use, the unsupervised categorization is completed and shown in Fig.3 Snow cover, mixed-cover forests, barren ground, low-density built-up areas, and water bodies were identified and classed to fit the SWAT LULC database.

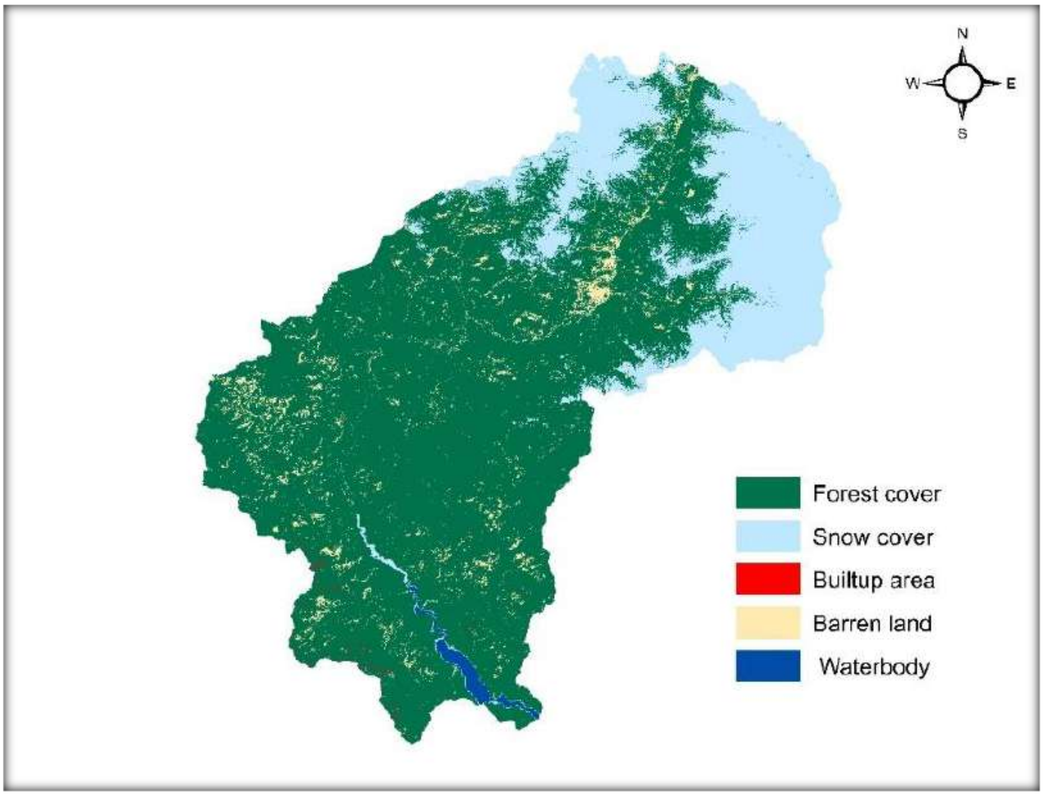


Fig. 3. LULC Map of Study Area

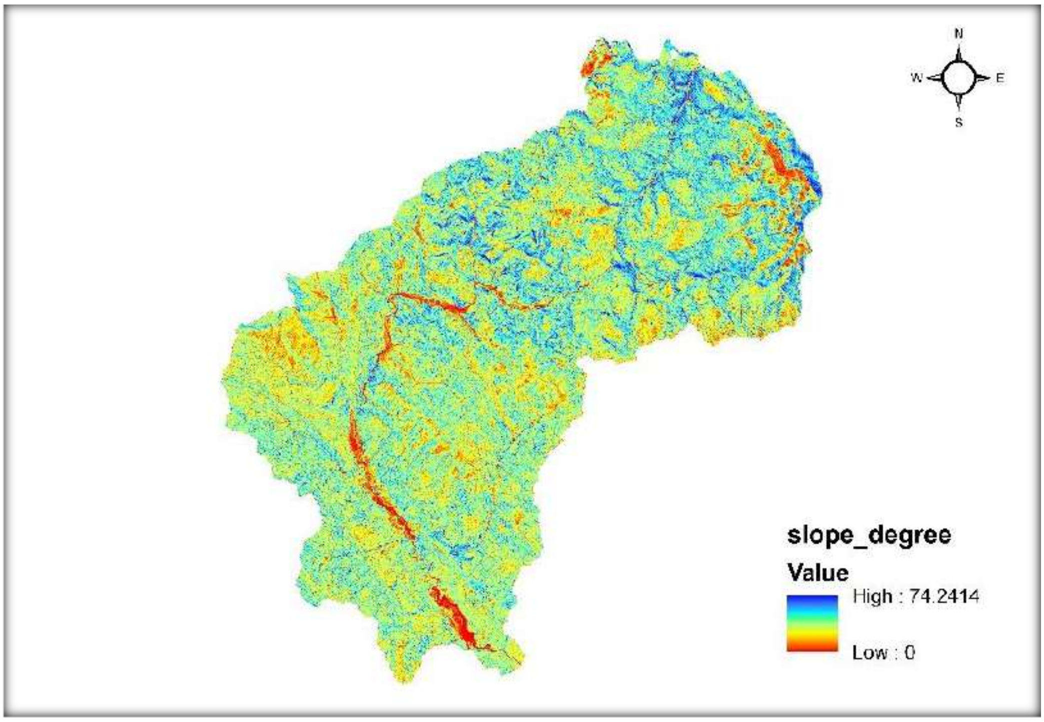


Fig. 4. Slope Map of Study Area

2.4.3 Soil data

The World Soil Database created by the Food and Agriculture Organization of the United Nations served as the primary source for the soil map of the basin (FAO-UN). This database offers a map of the world's soils. The study area's soil map was processed and trimmed. According to Fig. 3.44, two distinct soil classes have been identified in this study area.

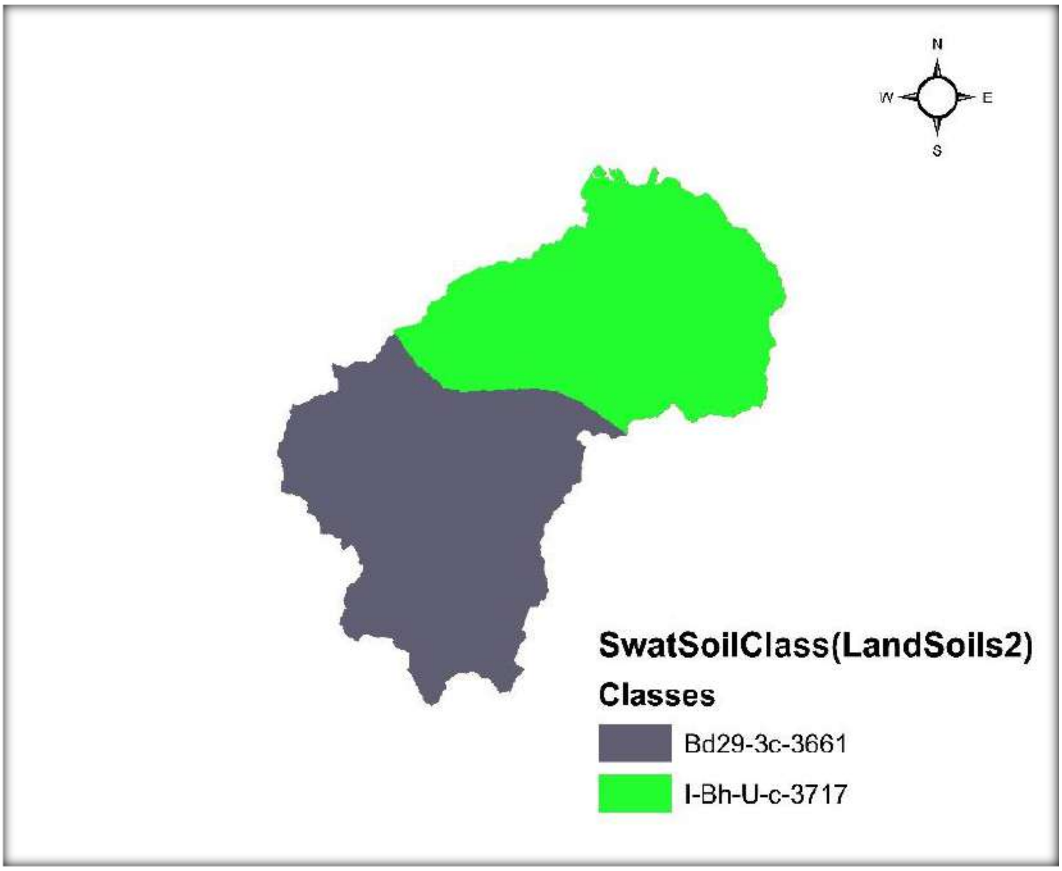


Fig. 5. Soil Map of Study Area

2.4.4 Weather data

SWAT requires daily and monthly meteorological data, which can be found in observed data sets or generated by weather generator models. Precipitation, minimum and maximum temperatures, relative humidity, wind speed, and solar radiation are among the climate factors taken into account in this study during the period 2000–2014. This information was all gathered from the Climate Forecast System Reanalysis (CFSR) website maintained by the National Centers for Environmental Prediction (NCEP). (referred “CFSR weather”) (https://globalweather.tamu.edu/#pubs).

Table 1. Watershed weather station information

Station	Longitude	Latitude	Elevation	From	To	Frequency
Tehri	78.4375	30.4423008	762	1979	2014	Daily
Sangrali	78.4375	30.75449944	1664	1979	2014	Daily
Sarun May Bandiyar	78.75	30.4423008	1929	1979	2014	Daily
Uttarkashi	78.75	30.75449944	3550	1979	2014	Daily
Gangotri	78.75	31.06679916	3714	1979	2014	Daily
Sankari Range	78.4375	31.06679916	4144	1979	2014	Daily

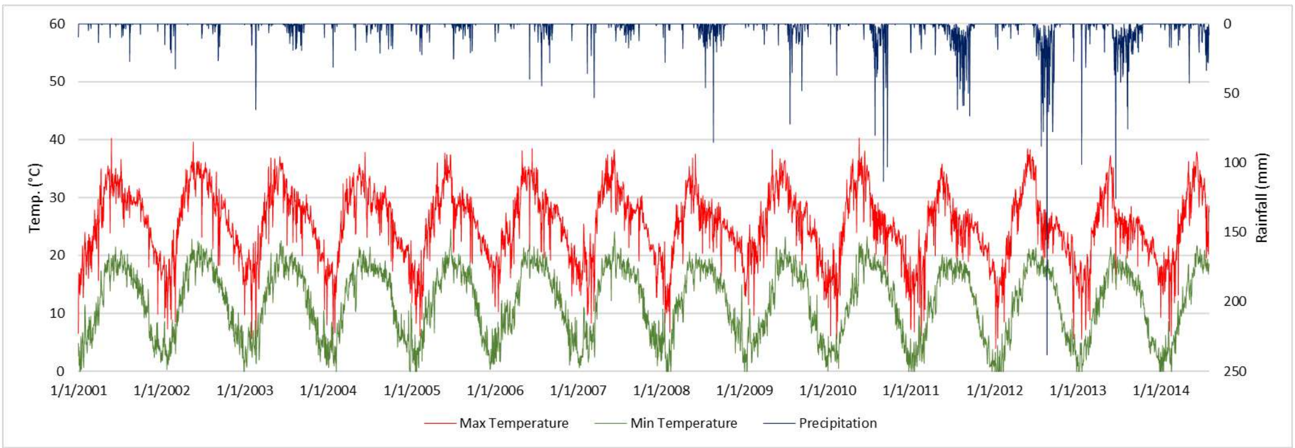


Fig. 6. Daily variation of Temperature and Rainfall at Tehri Station

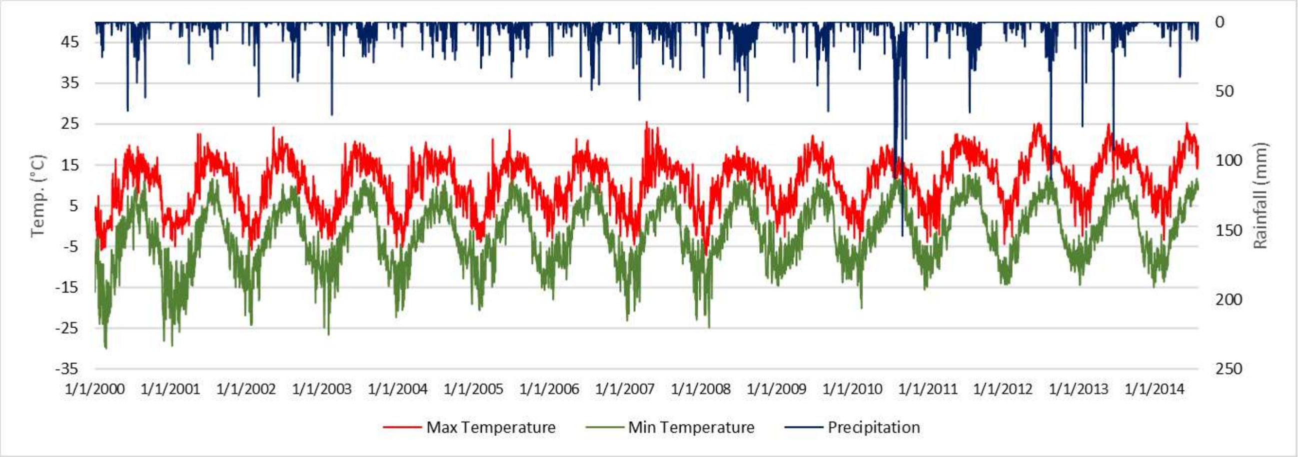


Fig. 7. Daily variation of Temperature and Rainfall at Uttarkashi Station

3. Results and Discussion

3.1. Standard SWAT Output

A watershed's average annual information, which includes a number of hydrological and water quality metrics, is provided via standard SWAT output. Table 2 lists several significant basin characteristics.

Table 2. Watershed Characteristics

Characteristics	Bhagirathi River Basin	
Land use/land cover	**LULC Classes**	**Area coverage (%)**
	Forest-Mixed (FRST)	73.19
	Water (WATR)	22.38
	Residential-Low Density (URLD)	0.12
	Spring Barley (BARL)	4.31
Soil Classification	**Soil Type**	**Area coverage (%)**
	Bd29-3c-3661	52.53
	I-Bh-U-c-3717	47.47
Slope Distribution	**Slope class limit (%)**	**Area coverage (%)**
	0-25	9.11
	25-50	32.27
	50-9999	58.62
Total Area (ha)	**251425**	

3.2. Validation and Calibration of SWAT Output

The calibration process assesses the suitability of a hydrological model for use. For the Bhagirathi River basin, the SWAT CUP calibration was performed for the years 2000-2010. The model was established in the initial two years (2000 and 2001) by accurately defining the internal hydrological compartments' conditions such as soil moisture content, groundwater store, etc. The input variables utilized for model calibration were CN, ALPHA BF, GW DELAY, and GW QMN. The SCS curve number is a significant determinant of soil permeability, soil moisture, and land use. It has been found that raising CN raises hydrograph spikes by decreasing infiltration and base flow. A clear indicator of how groundwater flow responds to variations in recharge is the base flow recession constant (ALPHA BF). The groundwater delay time is the period of time between water evaporating from the soil profile and entering the shallow aquifer (GW DELAY). The groundwater and vadose zones' hydraulic properties as well as the depth of the water table determine it.

The calibration findings reported in Figure 24 demonstrated that the observed peak value in years 2008 and 2010 differed significantly from the simulated peak value. The over prediction seen during these years could be attributed to the fact that SWAT is unable to simulate extreme events accurately and over predicts or under predicts large flows in the basin [25]. Past studies have also related over predictions and under predictions to spatial variability within a watershed [26] [18]. Results of the validation periods are shown in Figure 8. As was designated above, SWAT was unable to forecast extreme events during the calibration phase, which lasted from 2011 to 2013. This is also true of the validation phase, except that simulation is well synchronized with the measured values.

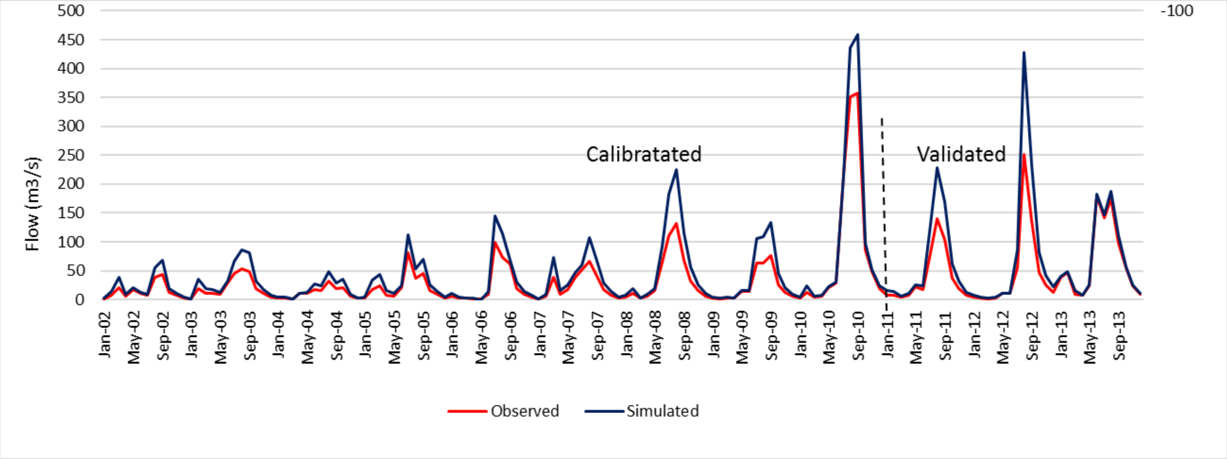


Fig. 8. Observed and Simulated Flow for Calibrated and Validated Period

Figure 9 portrays the graph comparing observed and simulated values against precipitation, indicating that the rainfall peaks closely correspond to both actual and modeled values. Figures 10 illustrate the linear regression graph between observed and simulated streamflow values during the calibration and validation periods, with R^2 values of 0.87 and 0.76, respectively. The SWAT simulations accurately reflect the peak-flows as well. This validates the SWAT model over the watershed for modeling discharge, which is also evident from the effectiveness measurements. The effectiveness measurements, R^2 and NSE values, are discovered to be 0.76 and 0.71, respectively, on a monthly timeframe. As a result, the model may be used to simulate discharge over the basin and evaluate how climate change would affect the hydrology of the watershed.

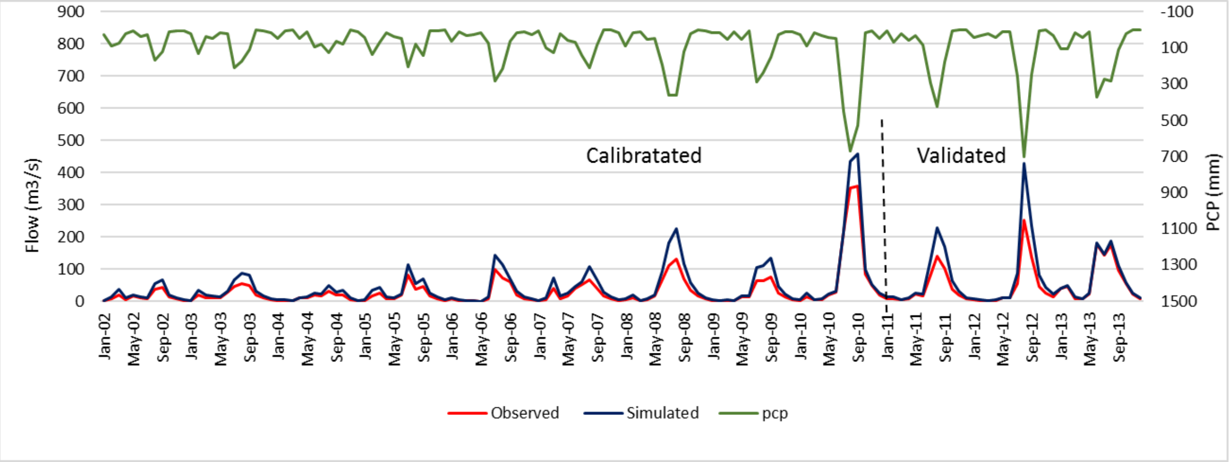
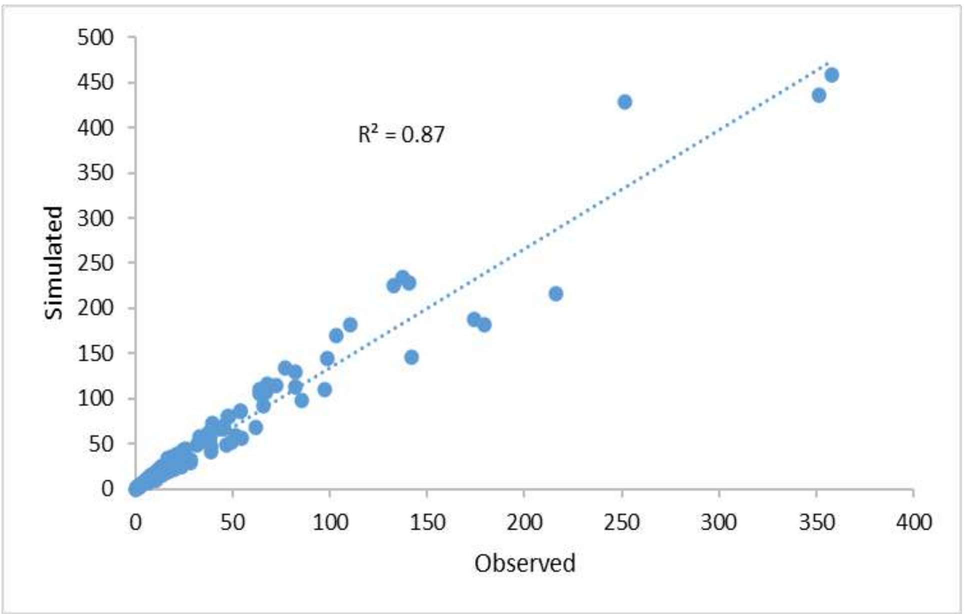


Fig. 9. Observed and Simulated Flow including Precipitation for Calibrated and Validated Period



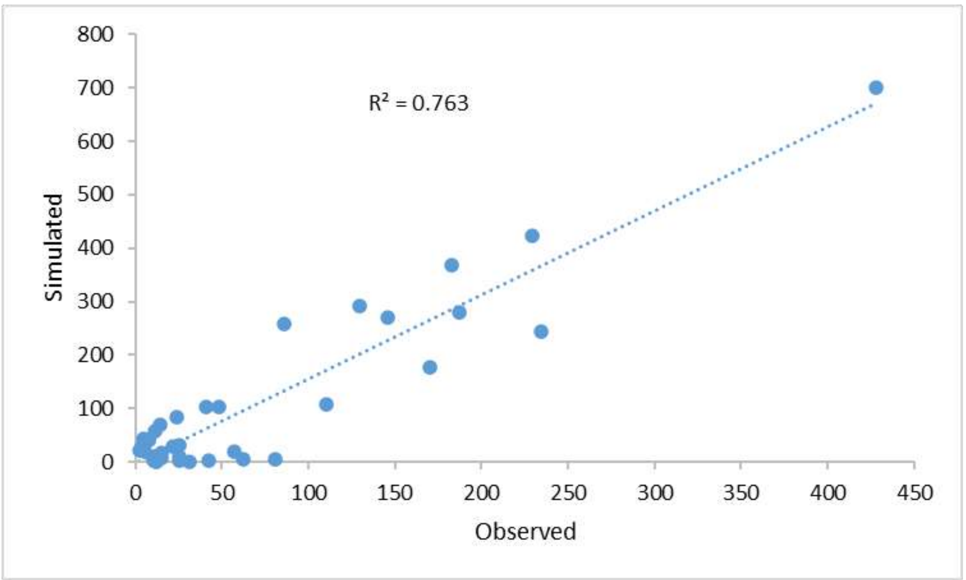


Fig. 10. R^2 values of calibration and validation period

Following calibration and validation, it was found that the R^2 value was, respectively, 0.87 and 0.76 for the calibration and validation periods. This suggests that the observed and simulated streamflow data show a very significant connection. It has a lower NSE value than R^2, but it is more than adequate, according to Moriasi et al., 2007 (NSE > 0.50). NSE **(**Nash Sutcliffe efficiency**)** was 0.83 and 0.71 for calibration and validation period respectively. Less NSE value than R^2 but it is more than satisfactory [27]. Lesser NSE value indicates that because it was considered as the main objective function during the simulation of observed data, whereas high R^2 implies that both are strongly correlated, while their magnitudes that varies greatly [28].

The percent of bias (PBIAS) calculated for calibration and validation was 6.4 and -15.7, respectively. The PBIAS value indicates that the calibration period was less overestimated than validation period, and both values are falls within satisfactory limits (PBIAS <20) [20]. The statistical significance of the NSE, R^2, PBIAS p-factor, and mean values are shown in Table 3. Due to the shorter duration of the validation period, the results show that the calibration period had less uncertainty than the validation period. For the calibration and validation period, the SWAT model's overall prediction of monthly surface runoff was exceptional.

Table 3. Model Performance Statistics Results

S.No.	Statistical parameters	Calibration (2000-2010)	Validation (2011-13)
1	R^2	0.87	0.76
2	p-factor	0.88	0.68
3	NSE	0.83	0.71
4	PBAIS	6.4	15.7
5	Mean (Simulated)	33.01	42.60
6	Mean (Observed)	35.26	50.56

Table 4. Statistics of Sensitivity Analysis

S.No.	Parameter	Description	Fitted Value	Min. value	Max. value
1	CN2.mgt	Curve number	-0.17	-0.2	0.2
2	ALPHA_BF.gw	Base flow alpha factor	0.125	0	1
3	GW_DELAY.gw	Ground water delay time	355.5	30	450
4	GWQMN.gw	A threshold minimum depth of water in the shallow evaporation coefficient	1.45	0	2

Table 5. Ranking of Most Sensitive Parameters

Rank	Parameter Name	P-Value	t-Stat
1	GW_DELAY.gw	0.072	-1.9315
2	ALPHA_BF.gw	0.2	-2.3398
3	GWQMN.gw	0.624	-0.4998
4	CN2.mgt	0.672	0.4315

After the successful calibration and validation, a global sensitivity analysis was conducted. Table 4 lists the sensitivity parameters taken into consideration and their fitted values. Table 5 displays the findings of the sensitivity analysis. GW DELAY, ALPHA BF, GWQMN, and CN2 were the most streamflow-sensitive parameters, with corresponding p-values of 0.072, 0.2, 0.624, and 0.672. More sensitivity is indicated by a p-value that is closer to 0. The quick changes in land use classifications are shown by GW DELAY's sensitivity. It results from the basin's seasonal change and snowfall. According to the sensitivity of ALPHA BF, infiltration, percolation, and baseflow are believed to be the main sources of water flow in this lowland region because of the shallow groundwater. The sensitivity of ALPHA BF suggests a prompt response and movement to groundwater replenishment because the basin is situated in a mountainous area. While CN2.mgt has a p-value of about 1, which means that it is not significantly different from zero.

4. Conclusions

This study's objective was to use ArcSWAT to create a hydrological model that would simulate the streamflow for the Bhagirathi River basin up to the Tehri dam. The effectiveness measurements ($R^2 = 0.76$, NSE = 0.71) taken throughout the validation period show that the model performed superbly in simulating streamflow. The calibrated and validated model will be helpful for the Bhagirathi River basin catchment's water resource planning and management. The data presented in this work; high-resolution remotely sensed data is useful for hydrological modeling across Bhagirathi River basin catchment. The study can be concluded in the following ways based on observations:

1. For the Bhagirathi River basin, it is revealed that the parameters GW DELAY, ALPHA BF, GWQMN, and CN2 are the sensitive parameters. Out of which, GW_DELAY is the most sensitive parameters.
2. The model worked well, as evidenced by the R^2 values of 0.76 during validation and 0.83 during calibration. Interesting, the NSE values for calibration and validation were 0.83 and 0.71, respectively, which is once more a good indicator for the applicability of the model.
3. The SWAT model gives strong simulation results of daily and monthly time steps despite data ambiguity, which is helpful for the basin's water resources management. Additionally, the modeling may be used to plan future dam building and manage flood disaster risk, which will help with the management of water resources in the Bhagirathi River basin and benefit the nation's sustainable development.
4. The SWAT model is adequate for streamflow prediction in the Bhagirathi River basin, according to the results of the SUFI-2 global sensitivity analysis.

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