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Soil erosion estimation using the SWAT model in Hathmati watershed of the Sabarmati river basin

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ABSTRACT

This study uses the soil and water assessment tool (SWAT) model to estimate surface runoff and soil erosion in the Hathmati watershed of the Sabarmati river basin in India, covering an area of 1,421.91 km². The SWAT model integrates meteorological data, topography, land use, soil characteristics, and climate data to assess soil erosion over 20 yrs from 2001 to 2020. The simulation includes a 2 yr warm-up, a 13 yr calibration, and a 5 yr validation phase. The model's accuracy is validated with coefficient of determination (R^2) and nash sutcliffe efficiency (NSE) values of 0.90 and 0.86, indicating acceptable performance. Results show that soil erosion rates in the Hathmati watershed range from 10 to 40 t $ha^{-1}yr^{-1}$, with rates exceeding 40 t in some years due to heavy rainfall. Variations in rainfall are the primary cause of differences in erosion rates. Structural and vegetative measures can be implemented to address these issues. The SWAT model is suitable for runoff and soil loss prediction in the Sabarmati river basin.

1 | INTRODUCTION

In recent decades, water-induced soil erosion has emerged as a significant global issue due to the declining ratio of natural resources to population and the effects of climate change (Terranova *et al.,* 2009). Soil erosion is the disintegration and removal of topsoil due to rainfall and surface runoff affecting the soil's nutrition level and any region's agricultural productivity. The estimated global average soil erosion rate is about 12 to 15 t $ha^{-1}yr^{-1}$ (Biggelaar *et al.,* 2003; Buraka *et al.,* 2022) resulting in a soil loss of approximately 0.96 to 1.20 mm from the land surface annually. In India, out of a total land surface of 328.80 M ha, 94 M ha are affected by water-induced soil erosion, 16 M ha by acidification, 14 M ha by flooding, 9 M ha by wind erosion, 6 M ha by salinity, and 7 M ha by a combination of these factors (Bhattacharya *et al.,* 2015). In a developing nation such as India, where agriculture plays a crucial role in the economy, the impact of soil loss, particularly the loss of top fertile soil, has a significant effect on agricultural output, land use intensity, and cropping patterns, all of which have significant environmental and economic consequences (Rajbanshi and Bhattacharya, 2020). In addition to reducing agricultural productivity, soil erosion leads to increased siltation in rivers, reservoirs, and wetlands, resulting in disasters like floods and droughts that threaten the ecology of affected areas (Jamal *et al.,* 2022).

Soil erosion is affected by several factors, including soil types, intensity of rainfall, topographic conditions and human activities (Makhdumi *et al.,* 2023). The physical characteristics of the soil are crucial in keeping the soil particles together, *viz.,* weaker soil types comprised of silty and sandy soil are more prone to erosion as the soil lacks the strength to bind the soil particles together owing to high runoff rate, while clayey soil is less prone to soil erosion (Ghosh *et al.,* 2022). Land use / land cover change (LU/LCC), such as alteration in agricultural practices, clearing of the forest, etc., have accelerated the rate of soil erosion (Guo *et al.,* 2019). Numerous research studies have found that soil loss is primarily caused by water, which is exacerbated by improper land use and management practices, including unscientific tillage and agricultural methods (Bhatt *et al.,* 2020).

Himanshu *et al.* (2019) applied the SWAT model to evaluate the best management practices to control sediment and nutrient loss control in the Marol watershed, Chhattisgarh. After successful calibration and validation, the model performance in simulating daily / monthly discharge and sediment was satisfactory. The study highlighted 12.2 t $ha^{-1}yr^{-1}$ annual average sediment yields besides evapotranspiration as a predominant phenomenon over the watershed (approx. 46.3 % of the annual average rainfall).

Estimating soil erosion is one of the major challenges in managing natural resources and environmental planning. Empirical models such as the revised universal soil loss equation (RUSLE) (Renard *et al.,* 1991) and the modified universal soil loss equation (MUSLE) are utilized for estimating soil erosion (Warjri, 2019). Computer simulation models are being used to predict soil loss for various land use and management practices, and they are gaining popularity. To forecast runoff, flooding, soil erosion, and nutrient transport in agricultural watersheds under different conditions, various hydrological models such as ANSWERS (Beasley and Huggins, 1980); CREAMS (Knisel, 1980); EPIC (Williams *et al.,* 1985); TOPMODEL (Beven and Kirkby, 1979); SHE (Abbott *et al.,* 1986); IHACRES (Jakeman and Hornberger, 1993); AGNPS (Young *et al.,* 1987); SWARB (Williams *et al.,* 1985); IHDM (Calver and Wood, 1995); SWM (Crawford and Linsely, 1966) and SWAT (Arnold *et al.,* 1996) have been established.

Among these models, the SWAT model is a physically based continuous model that is able to simulate surface runoff, sediment yield, and nutrient losses in all kinds of watersheds covering small (< 250 km^2) to large (> 2500 km^2) (Mehan *et al.,* 2017).

Estimating soil erosion is crucial for the Hathmati Watershed as it directly impacts land productivity, water quality, and overall watershed health. Understanding erosion patterns helps in the development of effective soil conservation and land management strategies to mitigate degradation. Moreover, accurate estimation allows for prioritizing vulnerable sub-catchments for targeted interventions, ensuring sustainable watershed management and protection of natural resources. This study aimed to estimate soil erosion in semi-arid areas of the Hathmati watershed within the Sabarmati river basin using the SWAT model to evaluate the effects of changing rainfall patterns. The objectives of this study include (i) identifying and delineating hydrological response units (HRUs) within the study area and (ii) estimating soil erosion rates using the SWAT model.

2 | MATERIALS AND METHODS

2.1 | Study Area

Hathmati river is a left-bank tributary of the Sabarmati river. Originating in the southwestern foothills of the Aravali range in Gujarat state, it flows southwest for 122 km before joining the Sabarmati on its left bank. This tributary drains an area of about 1421.91 km^2. The Hathmati basin exhibits the greatest spatial variation in rainfall compared to all other sub-basins within the Sabarmati basin. The location map of the Hathmati watershed, generated in Arc-GIS, is presented in Fig. 1.

The Hathmati basin experiences a tropical climate with three distinct seasons: monsoon from late June to Oct, *rabi* season (Nov to Feb), which is generally dry except for occasional rain in Nov and summer season from March to mid-June. Rainfall in the Hathmati basin occurs almost entirely during the monsoon season, with an average annual precipitation of approximately 860 mm, although significant regional variations exist. This watershed's diverse soil types and irrigation facilities enable it to support a wide variety of crops. The region primarily grows crops like paddy, maize, and millet during the *kharif* season, benefiting from the monsoon rains. In the *rabi* season, crops such as wheat, chickpea, mustard, and other pulses are commonly cultivated. Additionally, horticultural crops like vegetables, fruits, and spices are grown in certain watershed areas. Agriculture here relies significantly on both rainwater and irrigation from the Hathmati river and its associated water storage facilities.

HIGHLIGHTS

- SWAT model was evaluated for runoff and soil loss estimation in the Hathmati watershed of Sabarmati river basin of Gujarat, India.
- Over a 20 yr simulation period, the SWAT model achieved R^2 and NSE values of 0.90 and 0.86 and estimated soil loss rates of 10 to 40 t $ha^{-1}yr^{-1}$.
- Soil erosion rates varied mainly due to rainfall differences, highlighting the need for conservation measures in degraded sub-watersheds.

2.2 | Methodology

In the present study, the SWAT model is used to estimate soil loss, and Fig. 2 represents the flow chart of the methodology used in the study.

2.3 | Soil and Water Assessment Tool (SWAT)

The SWAT model is a semi-distributed, watershed-scale simulation model that uses daily time steps. It includes various components such as hydrology, meteorological parameters, soil information, crop growth, nutrients, pesticides, sediment yield, and agricultural management practices (Contractor *et al.,* 2024; Byakod *et al.,* 2017; Verma *et al.,* 2020). The hydrological components of the SWAT model are defined in eq. 1.

$$SW_f = SW_i + \sum_{i=1}^{t}(R - Q - E - W - Q_w) \quad ...(1)$$

Where, SW_f is the final soil water content (mm), SW_i is initial soil water content (mm) of the day *i, t* is time in days,

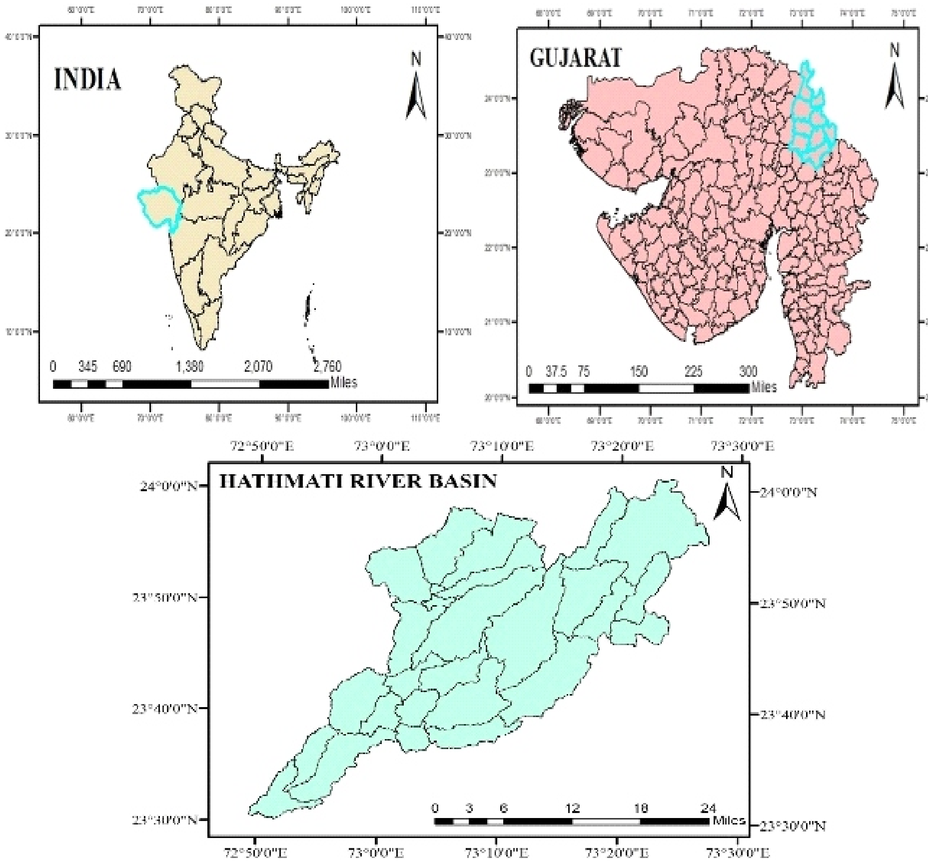

FIGURE 1 Hathmati watershed map

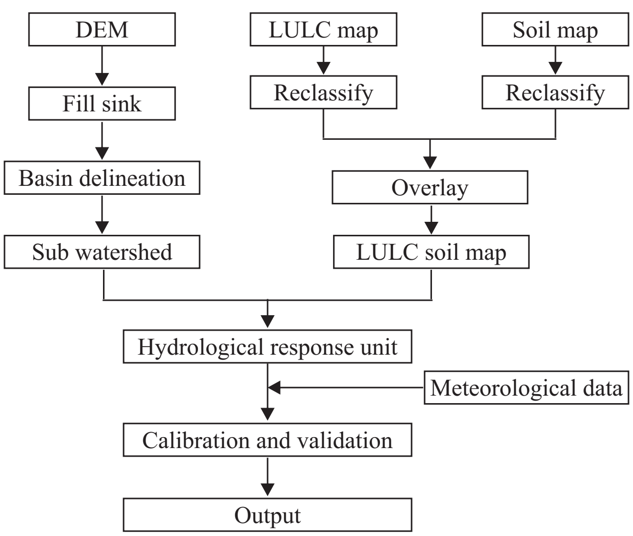

FIGURE 2 Flow diagram illustrating the methodology used to estimate soil loss in the Hathmati watershed

R is amount of precipitation (mm) on day i, Q is amount of surface runoff (mm) on day i, E is amount of evapo-transpiration (mm) on day i, W is amount of water entering the vadose zone from the soil profile (mm) on day i and Q_w is amount of return flow (mm) on day i.

Using daily or sub-daily rainfall quantities, SWAT simulates surface runoff volumes and peak runoff rates for each HRU using green and ampt infiltration technique or the soil conservation service curve number (SCS-CN) approach (Neitsch *et al.,* 2005).

The CN in the CN technique fluctuates nonlinearly with the soil profile's moisture content, reaching a minimum value as the soil profile gets closer to the wilting threshold and rising to almost 100 as the soil gets closer to saturation. Eq. 2 is used to determine the surface runoff.

$$Q = \frac{(R - 0.2S)^2}{R + 0.8S} \qquad R > 0.2S$$
$$Q = 0 \qquad R \leq 0.2S \qquad \text{...(2)}$$

Where, Q is daily surface runoff (mm), R is daily rainfall (mm), and S is a retention parameter.

The retention parameter S varies within a watershed because of variations in soils, land use management, slope, and changes in soil water content over time. The SCS-CN is used to determine the retention parameter 'S'.

$$S = 254\left(\frac{100}{CN} - 1\right) \qquad \text{...(3)}$$

The MUSLE, which is used to calculate soil erosion and sediment yield for each HRU, and represented by eq. 4.

$$SE = 11.8 * \left(Q_{surf} \cdot q_{peak} \cdot Area_{hru}\right)^{0.56} * K_{USLE} * P_{USLE} * C_{USLE} * LS_{USLE} * C_{FRG} \quad ...(4)$$

Where, SE is soil erosion load (MT), Q_{surf} is surface runoff volume (mm of water per ha), q_{peak} is peak runoff rate (m^3s^{-1}), $Area_{hru}$ is HRU area (ha), K_{USLE} is soil erodibility factor, P_{USLE} is support practice factor, C_{USLE} is cover and management factor, LS_{USLE} is a topographic factor, and C_{FRG} is the coarse fragment factor.

2.4 | Data Used

The SWAT model needs a variety of input data in order to estimate soil erosion, which includes (i) weather data, such as temperature, precipitation, solar radiation, wind speed, and relative humidity; (ii) topographic data, such as DEM; (iii) LU/LC maps; (iv) soil types and properties; and (v) river gauging data. These data allow the SWAT model to replicate the watershed processes affecting soil erosion. A DEM of 30 m resolution for Hathmati watershed was downloaded from the unites state geological survey (earth explorer) / shutter radar topographic mission (SRTM-www.srtm.csi.cgiar.org). Other data, such as meteorological data and river gauging data, for a span of 20 yrs (2001 to 2020) have been collected from the state water data center (SWDC), Gujarat. Table 1 shows details of the rain gauge stations that are located within the study area.

TABLE 1 Details of rain gauge stations

S.No.	Station name	Latitude	Longitude	Elevation (m)
1.	Badoli	23° 49' 30"	73° 04' 31"	217
2.	Bhiloda	23° 47' 00"	72° 56' 30"	230
3.	Mankadi	23° 41' 30"	73° 09' 40"	195
4.	Khandiol	23° 42' 00"	73° 03' 00"	185

2.5 | Model Performance Evaluation

The calibration and validation results are evaluated based on visual comparison and statistical criteria such as NSE, R^2, relative volume error (% error), root mean square error (RMSE) and mean absolute error (MAE), sum of square residuals (SSQR), p-factor and r-factor (Mamo and Jain *et al.,* 2013).

2.5.1 | Nash sutcliffe efficiency (NSE)

Nash Sutcliffe coefficient measures the efficiency of the model by relating its goodness of fit to the variance of the measured data. It ranges from - to 1. An efficiency of 1 corresponds to a perfect match of the simulated data with the observed one.

The value of NSE between 0.6 and 0.8 indicates reasonably good performance of the model, whereas a value between 0.8 and 0.9 indicates that the model performs well, and a value between 0.9 and 1 indicates that the model performs extremely well (Mamo and Jain *et al.,* 2013). The equation used to determine NSE is presented below.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(q_{oi} - q_{si})^2}{\sum_{i=1}^{n}(q_{oi} - \bar{q})^2} \quad ...(5)$$

Where, NSE is the nash sutcliffe coefficient, q_{si} is simulated flow (m^3s^{-1}), q_{oi} is observed flow (m^3s^{-1}) and $\bar{q}$ is the average of observed flow (m^3s^{-1}).

2.5.2 | Coefficient of determination

It provides a measure of how well the model replicates observed outcomes. The value of R^2 lies between 0 and 1. Zero means no correlation between observed and simulated data, whereas 1 indicates the predicted value is equal to that of the observed. The following equation is used to determine R^2.

$$R^2 = \frac{[\sum_{i=1}^{n}(q_{si} - \bar{q}_s)(q_{oi} - \bar{q}_o)]^2}{\sum_{i=1}^{n}(q_{si} - \bar{q}_s)^2 \sum_{i=1}^{n}(q_{oi} - \bar{q}_0)^2} \quad ...(6)$$

Where, R^2 is the coefficient of determination, q_{si} is simulated flow (m^3s^{-1}), qoi is observed flow (m^3s^{-1}), and q_o is the average of observed flow (m^3s^{-1}).

3 | RESULTS AND DISCUSSION

This study demonstrates that the application of the SWAT model in the study area effectively simulates hydrological parameters, surface runoff and soil erosion. The findings align with previous research highlighting SWAT's robustness in estimating surface runoff and soil erosion and predicting watershed hydrology under varying rainfall and climatic conditions. Studies across India, including in semi-arid, humid, and mountainous regions, consistently highlight SWAT's effectiveness in estimating soil erosion and its sensitivity to input parameters such as soil type, slope, rainfall, and land use patterns. These findings align with global research, affirming SWAT's utility in regions with complex hydrological conditions (Dutta *et al.,* 2018).

The SWAT model needs a variety of input thematic layers, *i.e.* a LU/LC map, soil map, slope map, and HRUs map, which have been prepared using the Arc-GIS environment to estimate surface runoff, soil erosion and delineate the Hathmati watershed.

3.1 | Watershed Delineation

The physiographic analysis based on catchment topography, is the initial stage in configuring the SWAT model for any study region. The watershed delineation was done by uploading the 30 m resolution DEM in Arc-GIS using the Arc-SWAT interface, and it is presented in Fig. 3.

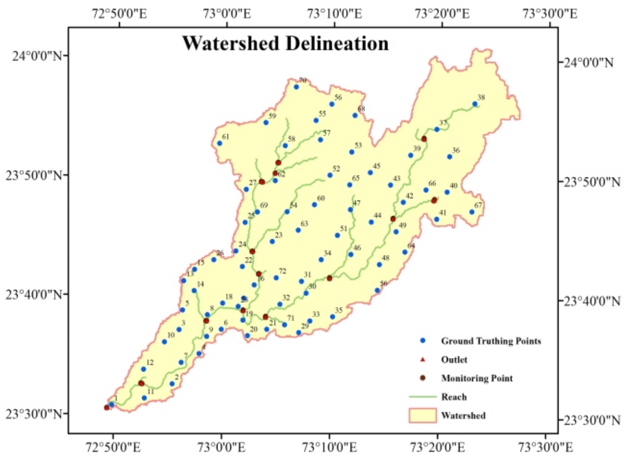

FIGURE 3 Map of watershed showing basin, major stream, outlet, monitoring points, and ground truth

Table 2 presents details of the Hathmati watershed's area, stream length, basin length, and elevations.

3.2 | Land Use/Land Cover (LU/LC) Map

Using supervised classification, land use patterns are determined by applying standard methods for analyzing remotely sensed data and interpreting satellite imagery. The standard method for determining land use patterns involves (i) data acquisition, (ii) pre-processing, (iii) analysis / classification and (iv) product generation / documentation (Roy *et al.,* 2010). Landsat 8 satellite imagery with a spatial resolution of 30 m and six spectral bands (Red, Green, Blue, NIR, SWIR 1 and SWIR 2) is used to create the study area's LU / LC map. These bands are chosen specifically for their ability to distinguish between different surface materials and plant types, which is necessary for proper land cover categorization. The 2020 yr Bhuvan data, an ISRO project that delivers high-resolution satellite photography of India, was used to confirm and update the LU/LC map. The LU/LC map of the study area is presented in Fig. 4 and summarized in Table 3. This indicates that the catchment has the highest area under agricultural land (52.89%), followed by forest land (28.29%). Random stratified sampling data are used to ensure the accuracy of observed classification maps by comparing satellite data with ground reality, producing accurate statistics. The LU/LC classification of this study closely aligns with the findings of Mohdzuned *et al.* (2016), who carried out their study in the Hathmati river basin.

A total of 72 ground truth points representing all LU/LC classes, are randomly selected from the study area for accuracy assessment, and their locations are shown in Fig. 3. Accuracy assessment is performed by calculating the kappa coefficient, overall accuracy, producer's accuracy, and user's accuracy. Overall accuracy is the most basic form of accuracy evaluation, giving a broad measure of how well a classification system performed across all categories or

TABLE 2 Characteristics of Hathmati watershed

Total watershed area (km^2)	1421.91
Total basin length (km)	369.12
Total stream length (km)	234.69
Minimum elevation (km)	81.00
Maximum elevation (km)	669.00
Mean elevation (km)	236.76

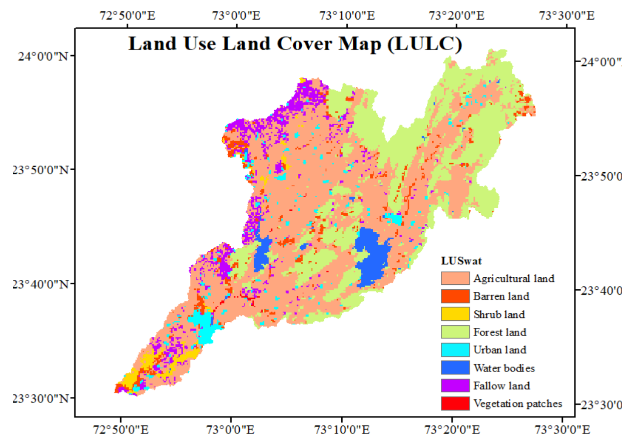

FIGURE 4 LU/LC map of the study area

TABLE 3 LU/LC classes of Hathmati watershed

S.No.	LU/LC class	Area (km^2)	Area (%)
1.	Agricultural land	752.05	52.89
2.	Barren land	54.74	3.85
3.	Shrub land	26.16	1.84
4.	Forest land	402.26	28.29
5.	Urban land	47.63	3.35
6.	Water bodies	46.92	3.30
7.	Fallow land	89.58	6.30
8.	Vegetation patches	2.56	0.18
	Total	1421.91	100.00

classes (Mehta *et al.,* 2014). The overall accuracy is calculated as 88.89%. The kappa coefficient is a statistical measure used to evaluate the reliability and accuracy of classification systems. It compares the observed and expected accuracy by considering both the actual agreement and the agreement that could occur by chance (Mehta *et al.,* 2014b) The value of kappa statistics is calculated as 0.847. Producer's accuracy is a measure used in classification accuracy assessments to indicate how well a specific class has been mapped or represented. It is the probability that a land cover type is correctly classified in the output map. User's accuracy is a measure used in the reliability of the classification from the perspective of the user, showing how likely it is that a pixel or sample classified into a certain category truly belongs to that category in reality (Mehta *et al.,* 2014b). The error matrix and the value of producer's and user's accuracy for various LU/LC classes, are presented in Table 4.

TABLE 4 Error matrix along with Producer's and User's accuracy

LU/LC class	Agricultural land	Barren land	Shrub land	Forest land	Urban land	Water bodies	Fallow land	Vegetation patches	Total
Agricultural land	22	0	1	0	0	0	0	0	23
Barren land	1	5	0	0	0	0	1	0	7
Shrub land	0	0	4	0	0	0	0	0	4
Forest land	0	0	0	14	0	0	0	0	14
Urban land	0	0	0	0	6	0	0	1	7
Water bodies	0	1	0	0	0	6	0	0	7
Fallow land	1	0	1	0	0	0	4	1	7
Vegetation patches	0	0	0	0	0	0	0	3	3
Total	24	6	6	14	6	6	5	5	72
Omission error	0.08	0.17	0.33	0.00	0.00	0.00	0.20	0.40	
Commission error	0.04	0.29	0.00	0.00	0.14	0.14	0.43	0.00	
Producer's accuracy	0.92	0.83	0.67	1.00	1.00	1.00	0.80	0.60	
User's accuracy	0.96	0.71	1.00	1.00	0.86	0.86	0.50	1.00	

Overall accuracy: 88.89%; Overall kappa statistics: 0.847

3.3 | Soil Map

Soil classification is derived from the world digital soil map developed by the Food and Agriculture Organization (FAO). The soil map of the study area is presented in Fig. 5 and summarized in Table 5. This indicates that the catchment has the highest area under the fine soil class (52.49%), followed by coarse loamy soil (18.84%).

3.4 | Slope Map

In watershed prioritization, slope is an important component. Steeper slopes tend to generate greater runoff, reduce infiltration, and consequently lead to increased soil erosion. Slopes are categorized according to the criteria outlined in the integrated mission for sustainable development (IMSD) document. The slope map of the study area is presented in Fig. 6 and summarized in Table 6.

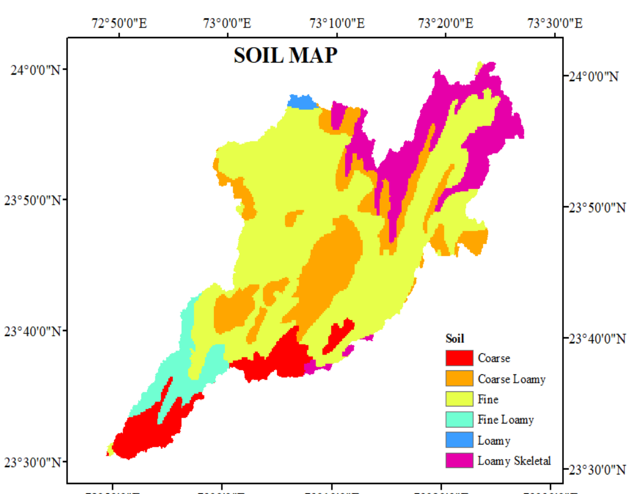

FIGURE 5 Soil map of the study area showing the classification of soil

TABLE 5 Soil classes of Hathmati watershed

S.No.	Soil class	Area (km^2)	Area (%)
1.	Coarse	117.02	8.23
2.	Coarse loamy	267.89	18.84
3.	Fine	746.36	52.49
4.	Fine loamy	79.34	5.58
5.	Loamy	7.68	0.54
6.	Loamy skeletal	203.62	14.32
	Total	1421.91	100.00

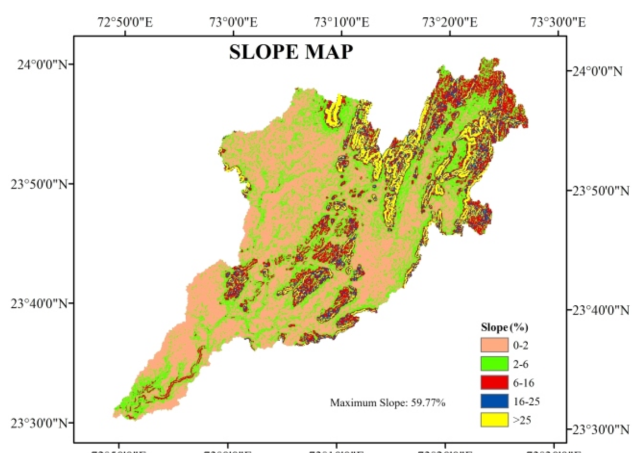

FIGURE 6 Slope map of the study area

TABLE 6 Slope classifications

Slope class	Slope class (%)	Area (km^2)	Area (%)	Slope classification
1	0 - 2	644.27	45.31	Level
2	2 - 6	398.13	28.00	Undulating
3	6 - 16	198.93	13.99	Rolling
4	16 - 25	81.19	5.71	Hilly
5	> 25	99.39	6.99	Steep
	Total	1421.91	100.00	

3.5 | Hydrological Response Units (HRUs)

HRUs are fundamental components in SWAT that represent unique combinations of land use, soil type, and slope within a watershed. The land use, soil, and slope data layers are integrated with Arc-SWAT to create a composite map for HRUs. Threshold values for land use, soil, and slope have been set to determine the level of detail for HRU creation. These HRUs are crucial for simulating the hydrologic and environmental processes at a fine spatial resolution. The model suggests 30 HRUs to delineate each sub-basin in the current study up to the outlet point using the current data available. Fig.7 represents the map of HRUs' present in the study area.

3.6 | Model Calibration and Validation

The objective of calibration and validation is to maximize the model efficiencies and, finally, use the parameter values obtained through those calibration techniques. Santhi *et al.* (2001) and Neitsch (2005) both give thorough explanations of the SWAT model calibration procedures and definitions of the various calibration parameters. Tejaswini and Sathian (2018) calibrated and validated the SWAT model using the SUFI-2 algorithm for the Kunthipuzha basin, Kerala. The model demonstrated strong performance with an R^2 of 0.82 and NSE of 0.81 for calibration, indicating a high degree of correlation and predictive accuracy between the observed and simulated data. The model performed well, with an R^2 of 0.88, showcasing an even better correlation, though the NSE slightly decreased to 0.73. The results showed good performance of model prediction over the entire catchment. The study showed that SUFI-2 is convenient and easy to use over the other automatic calibration techniques.

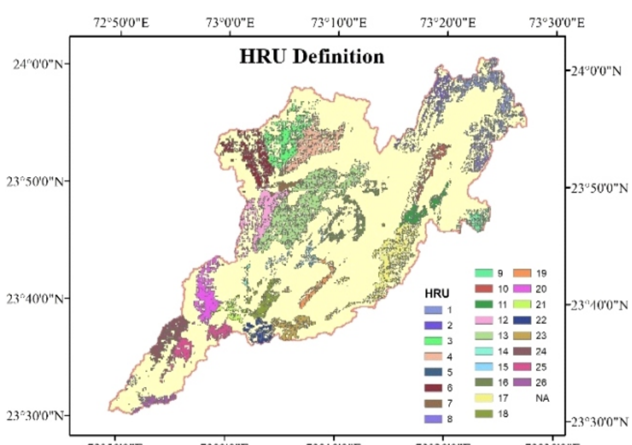

FIGURE 7 Map of study area showing HRUs

For the present study, the model is adjusted and calibrated for various parameters, as outlined in Table 7 and Fig. 8 illustrates how the SUFI-2 algorithm integrates the observed data.

A total of 50 simulations have been conducted to get calibrated values for each of the six parameters. The updated parameter values are then used for validation. The value of model performance indices during the calibration and validation periods are shown in Table 8. The values of R^2 and NSE are obtained as 0.90 and 0.86 for model calibration. The NSE and R^2 exhibit similar values for both calibration and validation. Both the values are positive, which falls into the zone of acceptability of the model.

The R^2 and NSE are used to assess the model performance. In general, model simulation can be judged as satisfactory if NSE > 0.50 and the typical value of R^2 is greater than 0.5 for stream flows (Byakod *et al.,* 2017). Based on the obtained results, the model is considered valid, and further analysis of its output has been conducted. The SWAT model's observed rainfall and simulated rainfall values agree reasonably well. Fig. 9 shows the comparison between observed and simulated rainfall values.

3.7 | Estimation of Surface Runoff and Soil Erosion

Fig. 10 presents the values of key hydrological parameters obtained from the SWAT model. The simulated average annual precipitation is 777.70 mm, and surface runoff and evapotranspiration are 178.53 and 573.50 mm, respectively.

The SWAT model result shows that the soil erosion rate ranges from 10 to 40 t $ha^{-1}yr^{-1}$ in the Hathmati watershed. Due to high rainfall, soil erosion rates of more than 40 t $ha^{-1}yr^{-1}$ were estimated in 2005, 2006, 2007, 2009, 2010 and 2014. The estimated value of rainfall, surface runoff, and soil erosion rates from the SWAT model for 20 yr periods is shown in Table 9.

The highest soil erosion was estimated at 158.90 t ha^{-1} in 2006, with an observed rainfall of 1640.55 mm. The lowest is estimated at 1.71 t ha^{-1} in 2018, with an observed rainfall

TABLE 7 Parameters used in the calibration of the model

S.No.	Parameter name	Parameter description	Unit	Range	Fitted value
1.	CN2.mgt	Curve number	-	35-98	84.29
2.	ALPHA_BF.gw	Base flow recession constant	days	0-1	0.70
3.	GW_DELAY.gw	Delay time for aquifer recharge	days	0-500	250
4.	USLE_K.sol	USLE equation soil erodibility (K) factor	-	0.02-0.65	0.335
5.	SURLAG.bsn	Surface runoff lag time	-	0.05-24	18.025
6.	SOL_K.sol	Saturated hydraulic conductivity	mm/hr	2000	172

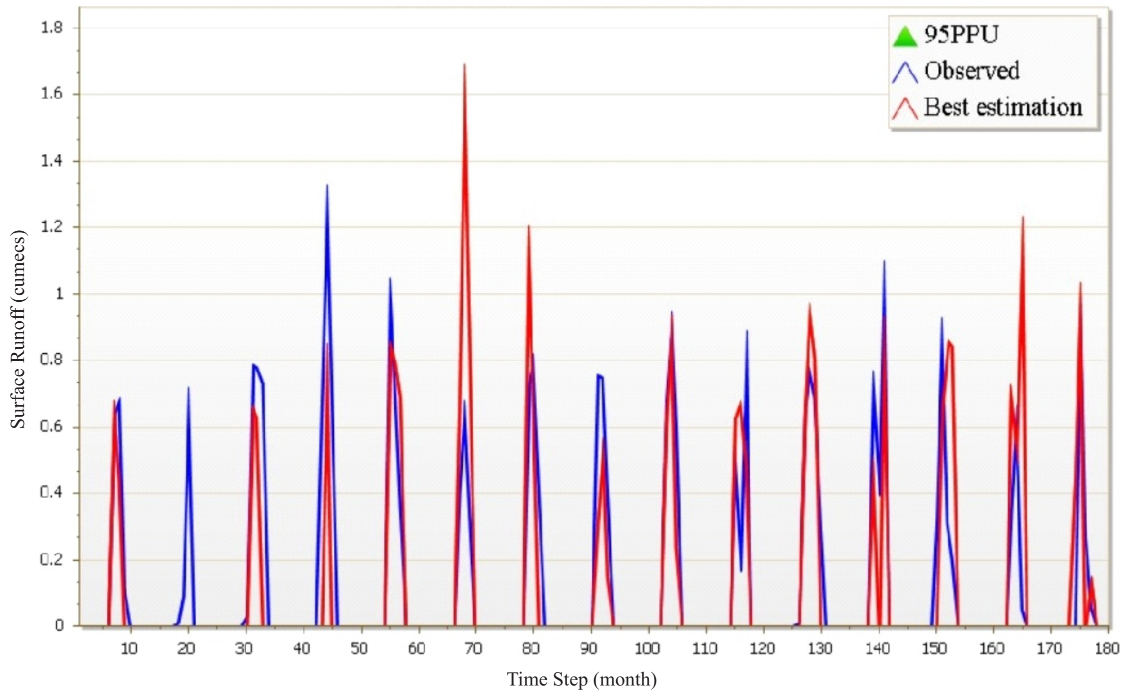

FIGURE 8 SWAT-CUP calibration for surface runoff

TABLE 8 SWAT model performance indices during calibration and validation periods

Performance indices	Model calibration	Model validation
R^2	0.90	0.85
NSE	0.86	0.77

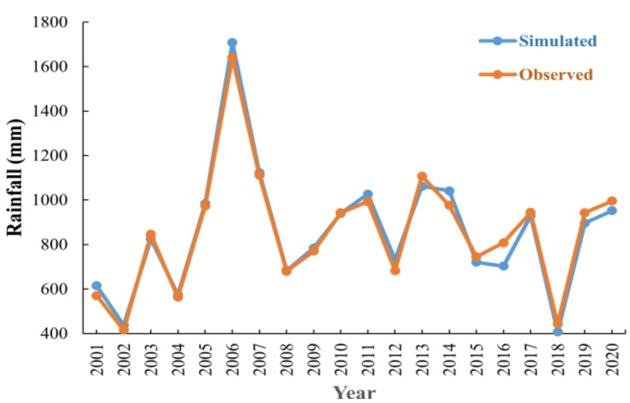

FIGURE 9 Graph illustrates the comparison between observed and simulated yearly rainfall

of 442.41 mm. The average annual soil erosion is estimated at 36.43 t ha^{-1}. The correlation between rainfall and soil erosion is presented in Fig.11, indicating that an increase in rainfall is associated with a rise in soil erosion.

Structural and vegetative measures can be implemented to address identified problems effectively. Structural interventions like check dams, percolation tanks, and contour bunding can help reduce surface runoff, enhance groundwater recharge, and control soil erosion. Vegetative measures, such as afforestation, agroforestry, and grassland management, can stabilize soil and improve biodiversity.

4 | CONCLUSIONS

This study uses the SWAT model to present the simulation of surface runoff and soil erosion for the Hathmati watershed in the Sabarmati river basin. The analysis demonstrates that the SWAT model is an effective tool for estimating surface runoff and soil erosion, providing valuable insights for watershed management. The simulated rainfall values closely matched the observed rainfall data, indicating the high reliability of the SWAT model. The model results showed that soil erosion rates in the Hathmati watershed ranged between 10 and 40 t ha^{-1}yr^{-1}. The highest soil erosion was estimated at 158.90 t ha^{-1} in 2006, with an observed rainfall of 1640.55 mm. In contrast, the least value of soil erosion is estimated as 1.71 t ha^{-1} in 2018, with an observed rainfall of 442.41 mm, which indicates a strong correlation between rainfall and soil erosion.

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DATA AVAILABILITY STATEMENT

The data presented in this study are available on request from the corresponding author.

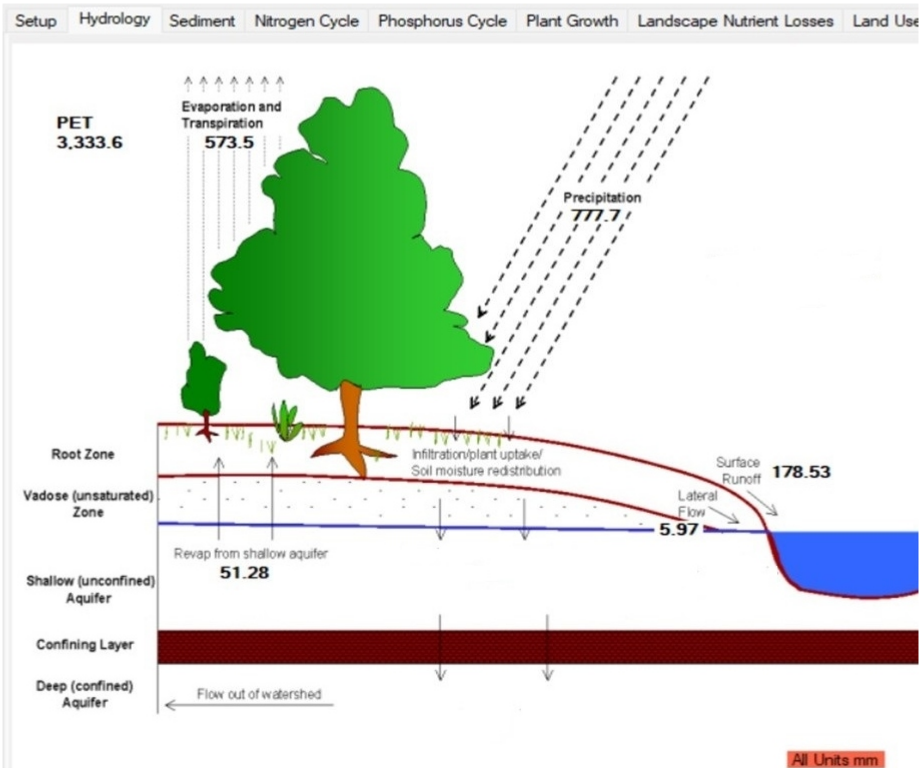

FIGURE 10 Hydrology of Hathmati watershed

TABLE 9 Estimated value of surface runoff and soil erosion from SWAT model

Year	Rainfall (mm)	Surface runoff (m^3sec^{-1})	Soil erosion ($t\ ha^{-1}$)
2001	614.51	5.26	17.79
2002	537.82	3.22	11.71
2003	825.27	9.39	32.42
2004	573.69	4.95	18.69
2005	983.89	16.93	59.58
2006	1707.91	42.79	158.90
2007	1123.57	19.98	49.77
2008	683.86	7.28	21.38
2009	783.78	12.70	54.23
2010	939.82	12.70	44.11
2011	1027.11	17.21	34.54
2012	731.82	11.70	23.44
2013	1062.24	15.38	30.6
2014	1040.85	21.04	49.48
2015	720.39	12.58	28.92
2016	703.21	6.95	17.01
2017	929.06	13.46	33.56
2018	407.35	0.95	1.71
2019	897.03	8.29	22.56
2020	951.84	8.71	18.25

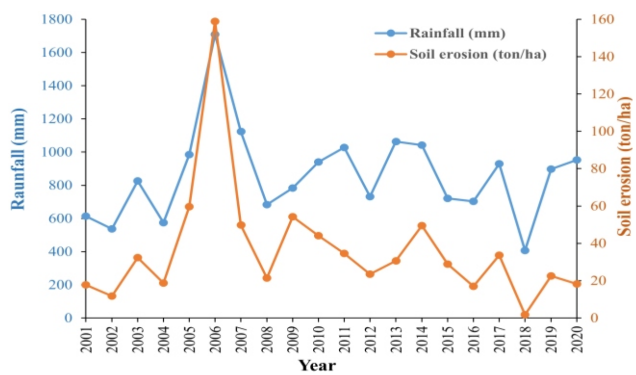

FIGURE 11 Correlation between estimated rainfall and soil erosion from SWAT model

CONFLICT OF INTEREST

The authors declare no conflict of interest related to this study.

AUTHOR'S CONTRIBUTION

BCC: initial idea, data curation, data analysis, conceptualization, model preparation, writing the original draft. BGB: writing validation, visualization, reviewing, and editing.

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