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Reshma B Kadlag
Ph. D. Scholar, Department of Soil and Water Conservation Engineering, Dr. A. S. College of Agricultural Engineering and Technology, Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra, India

Dr. Virendra N Barai
Professor, Department of Soil and Water Conservation Engineering, Dr. A. S. College of Agricultural Engineering and Technology, Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra, India

Dr. Bhau K Gavit
Associate Professor, Department of Soil and Water Conservation Engineering, Dr. A. S. College of Agricultural Engineering and Technology & Deputy Director of Research, Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra, India

Dr. Suhas K Upadhye
Associate Professor, Department of Agricultural Meteorology, College of Agriculture, Pune, Maharashtra, India

Dr. Anil G Durgude
Ex-Analytical Chemist, Micronutrient Research Scheme, Department of Soil Science & Agricultural Chemistry, Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra, India

Dr. Mahesh R Patil
Professor, Department of Statistics, Post Graduate Institute, Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra, India

Corresponding Author:
Reshma B Kadlag
Ph. D. Scholar, Department of Soil and Water Conservation Engineering, Dr. A. S. College of Agricultural Engineering and Technology, Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra, India

Applications of SWAT (soil and water assessment tool) model: A systematic review

Reshma B Kadlag, Virendra N Barai, Bhau K Gavit, Suhas K Upadhye, Anil G Durgude and Mahesh R Patil

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Abstract
Two important resources for human existence on the earth are land and water. It demands adequate management to obtain maximum utilization. The use of hydrological models for management of watershed resources is becoming more prevalent in decision-making processes. SWAT (Soil and Water Assessment Tool) is a promising model for simulating runoff, sediment and nutrient transport and erosion under various management scenarios. This work provides an overview of the advancements made in hydrological modeling using SWAT in previous studies. Numerous hydrological phenomena have been evaluated across a variety of study areas with the use of the SWAT model. Many investigations, including those on streamflow and land use planning, have employed the SWAT model with extremely effective implementation, as demonstrated by the reviews examined in this study. Thus, to review the studies conducted by different researcher's using the SWAT is the primary objective of this paper. This research focuses on the literature on SWAT model applications in India.

Keywords: Hydrological modeling, SWAT, watershed, HRUs, SWAT-CUP, SUFI-2

1. Introduction

To ensure long-term food production and environmental health, sustainable practices are essential to effective natural resources management in agriculture. New developments in technology have recently been demonstrated to be essential for natural resources and also help to protect biodiversity, maximize resource usage and increase the resilience of farming systems to climate change. Hydrological modeling, which simulates water flows and responses, is a crucial tool for natural resources management, helping to analyze the impact of changes and inform decisions for management of water resource, flood control, and protection of environment.

Hydrological modeling is one such technique that primarily consists of conceptual, and physically based models and empirical models. Conceptual models can be classified into two categories: distributed models and lumped models. The lumped models are unable to accurately depict the changes brought about by regional variations in runoff and nutrient flows (Jiang *et al.* 2017; Wang *et al.* 2019) [13, 41]. However, in distributed models, the entire catchment area is divided into several sub-watersheds, resulting in a final simulation result that is significantly closer to the observed results. Distributed hydrological modeling is increasingly important for development, use and management of natural resources since it can adequately depict the temporal and spatial and hydrological processes.

SWAT is one of the distributed models that many hydrologists, civil engineers, and researchers in India and around the world have been using. SWAT simulates the hydrological processes that take place in river basin catchments by utilizing a variety of hydrological parameters. The model was designed to analyze water resources and estimate the impacts of changes of land use land cover, land management techniques on soil erosion, sedimentation as well as non-point source pollution on watersheds or larger river basins (Gassman *et al.* 2007) [10]. Thus, this study's main objective is to review the research done in India utilizing the SWAT in order to manage natural resources efficiently for a sustainable future.

2. Setup, calibration and validation of SWAT model

The USDA-Agricultural Research Service developed SWAT, the physically based, continuous, deterministic, watershed-scale simulation model (Arnold *et al.*, 1998; Neitsch *et al.*, 2005) [3, 22]. The model simulates the quantity and quality of surface and ground water at the size of small watersheds to large river basins.

The SWAT model divides hydrology of watershed into two main sections: i) land phase of the hydrologic cycle, determine the quantity of water, sediment, nutrient and pesticide loadings to the main channel in each sub-watershed and, ii) routing phase, which simulate movement of water, sediments, etc. to the outlet of watershed through the channel network.

The hydrologic cycle as simulated by SWAT is based on following water balance equation:

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

Where, SW_t is the final soil water content, SW_0 is the initial soil water content, t is the time in days, R_{day} is the daily precipitation, Q_{surf} is the daily surface runoff, E_a is the daily evapotranspiration (ET), W_{seep} is the daily water entering the vadose zone from the soil profile and Q_{gw} is the daily return flow, all units in mm.

SWAT is distributed model, which divide the watershed into multiple sub-watersheds, which are further sub-divided into number of HRUs (Hydrologic Response Units) which consist of homogeneous land use, management and soil characteristics to increase model simulation accuracy. Watershed DEM (Digital Elevation Model), land use map, soil type, attribute table, meteorological data, and observed data, etc. are among the data needed for setup of model.

The first stage in SWAT's calibration and validation procedure is to identify sensitive parameters for a specific watershed or sub-watershed. Using sensitivity analysis or expert judgment, the user chooses which variables to change. Sensitivity analysis is the process of determining the rate of change in model output with respect to model inputs (parameters). The second step is calibration, which is an attempt to better parameterize a model to a specific set of local conditions, hence minimizing prediction uncertainty. In order to calibrate a model, values for its input parameters are carefully chosen, and the model's output (predictions) for a given set of assumed conditions are compared to the data that was observed under the same conditions. Validation for the component of interest (such streamflow or sediment yield) is the last step. The process of proving that a site-specific model can provide simulations that are adequate sufficient is known as model validation.

SWAT-CUP (SWAT- Calibration and Uncertainty Programme) is a program for the calibration of SWAT model. SUFI-2 (Sequential Uncertainty Fitting-2) algorithm is a widely employed approach and is an automated system that calibrates and validates the hydrological parameters and evaluates the sensitivity and uncertainty analysis and parameterization (Abbaspour *et al.*, 2007) [1].

The performance of SWAT model was assessed globally using R^2 (Coefficient of determination), NSE (Nash Sutcliff Efficiency), RSR (Root Mean Squared Error-observations standard deviation ratio), and PBIAS (Percentage of Bias) with the evaluation following guidelines of Moriasi *et al.* (2007) [20].

3. Applications of SWAT

3.1 SWAT for streamflow simulation

The primary goal of hydrological modelling is to quantify a watershed's hydrologic response to climatic parameters, management conditions, soils, and land use, which is useful for water resource planning, pollution control, flood forecasting, and other applications.

In India, SWAT model has been utilized for plain regions to mountainous region for simulating the streamflow and surface runoff. Santra and Das (2013) [29] used SWAT model to estimate future runoff potential for Chilika Lagoon, India. The NSE of simulated monthly surface runoff was 0.72 and 0.88 during calibration and validation, respectively indicating good model performance. Results indicated about 60% of precipitation becomes runoff, carrying significant sediment to Chilika Lake. Thus, implementing soil conservation measures could reduce sediment load and protect the lagoon ecosystem.

Varma and Zha (2015) [39] evaluated the streamflow in Baitarani watershed using SWAT. During calibration and validation, the model accurately reproduced streamflow on a daily (NSE=0.86 and 0.84) and monthly (NSE=0.95 and 0.93) basis. They concluded that SWAT is appropriate for simulating streamflow and has the potential to be implemented in Baitarani River Basin and other watersheds in India.

Another study conducted by Gavit *et al.* (2017) [11] for upper Godavari sub-basin to estimate the surface runoff during 1994 to 2014 using SWAT. R^2 for calibration and validation were 0.81 and 0.84, respectively for study area. The results showed that model performance for simulating runoff at daily time basis was satisfactory. In addition, a fully validated SWAT model can be utilized efficiently to test watershed management scenarios.

Kumar *et al.* (2017) [16] employed SUFI-2 algorithm to identify sensitive parameters, calibrate, and validate the SWAT for an agricultural-dominated watershed (Tons River Basin). The model was calibrated from 1979 to 2000, and validated from 2002 to 2011. During calibration, the R^2, NSE, PBIAS, and RSR were 0.74, 0.73, -3.55, and 0.54, respectively, and during validation, the values were 0.75, 0.69, 18.55, and 0.56, indicating good model performance for monthly streamflow simulation.

The effectiveness of SWAT in simulating streamflow in Bina basin (Madhya Pradesh, India) was examined in a study by Teshome *et al.* (2020) [37]. The model's performance was rated "satisfactory" for daily and "very good" for monthly simulations. According to model calibration results, the daily and monthly simulations had R^2 values of 0.66 and 0.96, respectively, and NSE values of 0.65 and 0.94. During model validation, the daily and monthly simulations had R^2 of 0.65 and 0.72, respectively, with corresponding NSE of 0.58 and 0.72. The efficiency of SWAT in simulating streamflow in the Bina basin was shown in this study.

To estimate monthly snowmelt contribution to runoff, Biswas *et al.* (2024) [6] used SWAT for Upper Alaknanda River basin, India. Model performed satisfactorily during calibration (2005-2012) and validation (2013-2017). Spatiotemporal evaluation showed April month had the highest snowmelt contribution to runoff (59.76%). The SWAT model effectively estimates snowmelt in upper Himalayan regions using satellite-based meteorological data. Thus, the above literature suggests SWAT is a promising tool for diverse environmental and climatic conditions for simulating the runoff.

Malik *et al.* (2022) [19] calibrated and validated multi-site models over monthly time steps in the southeastern Kashmir Valley using SUFI-2. According to the results, the monthly streamflow model performed exceptionally well for calibration, with R^2 values of 0.89, 0.85, and 0.89 and NSE values of 0.73, 0.72, and 0.83. But the monthly simulation validation results also showed good model performance for flow rates, with NSE values of 0.76, 0.52, and 0.56 and R^2 values of 0.86, 0.81, and 0.80.

Barman *et al. (2023)* [5] investigated ability of SWAT to simulate streamflow of Periyar River basin, India. The model for the basin performed "well" according to the four statistical performance indices employed in this work for calibration and validation: R^2 was 0.70 and 0.70, NSE was 0.70 and 0.68, PBIAS was 3.8 and -9.7, and RSR was 0.55 and 0.56. They demonstrated how the model's performance may be significantly enhanced by calibrating using the SUFI-2 technique.

Poojashree *et al.* (2022) [27] examined hydrology of a complex environment in Kollur River Basin, Karnataka and calibrated and validated the model using SUFI-2 algorithm. This study considered 14 important hydrologic parameters. They showed that streamflow values produced by the model and those observed were fairly accurate.

Swain *et al*. (2022) [36] applied SWAT for Tehri reservoir catchment, India (lower Himalayan region). The SWAT model is used for 12 years (2006-2017), including warm-up, calibration, and validation periods in 2006, 2007-2013, and 2014-2017, respectively. The model performs exceptionally well in streamflow simulation, according to the results. NSE and R^2, two efficacy indicators are found to be 0.83 and 0.84, respectively. Water resources engineers will find the data presented in this paper useful for hydrologic modeling across hilly catchments.

3.2 SWAT for sediment yield simulation

Soil is a crucial natural resource, supplying raw materials, food, and fiber. It also maintains biodiversity, regulates water and climate, and filters pollutants-essential for ecosystems and human health. To support life, soil provides vital nutrients like carbon, nitrogen, and phosphorus. However, the most productive surface layer is constantly degraded by slopes and heavy rainfall. This issue has worsened, disrupting the environment, economy, and ecology. In recent decades, hydrological models have helped analyze this problem by forecasting silt levels and their entry into water bodies.

Chandra *et al.* (2014) [7] estimated the sediment yield in the Upper Tapi catchment's Burhanpur sub-basin using SWAT. The basin's hydrological parameters, land cover, and soil characteristics were wildly irregular. Twelve years of observed surface runoff and sediment load data at the basin outlet were used to calibrate and validate the model. It was determined that the NSE and RSR values for sediment yield were within acceptable limits at 0.85 and 0.36, respectively.

Assessment of sediment yield in Malaprabha sub-basin, Karnataka is carried with SWAT model (Patil *et al*., 2016) [6]. The model performance was found good with NSE and R^2 values of 0.5216 and 0.6021 for calibration period (1981-1985) and 0.6258 and 0.6997 for validation period (1986-1989), respectively. By this study, understood that model with corresponding optimum set of parameters is ready to predict sediment yield, which could be useful for future designing and management in mitigating issues of erosion and sedimentation.

Himanshu *et al.* (2017) [12] predicted sediment yield in Ken basin, Madhya Pradesh with SWAT model. Observed discharge and sediment data from the Banda site were used to calibrate and validate model on monthly and daily time steps. Daily sediment simulation was significant, with R^2 = 0.429 for calibration and 0.379 for validation, while monthly simulation was excellent, with R^2 = 0.748 and 0.721, respectively. With average annual sediment yield of 15.41 t/ha/yr, basin is classified as highly erodible.

A study by Sabale *et al.* (2023) [28] predicted sediment load in Koyna basin, Maharashtra. The basin experiences significant soil erosion due to periodic floods and landslides. SWAT model was calibrated (2013-2017) and validated (2018-2020) using the SUFI-2 algorithm of SWAT-CUP. Calibration and validation showed good performance with acceptable R^2, NSE, and PBIAS values. Erosion distribution across sub-basins revealed sub-basin 17 had the highest sediment yield (145 t/ha/year), while sub-basins 1, 9, 12, and 16 had the lowest. To reduce erosion and sediment transfer, these sub-basins urgently need soil and water conservation measures.

Using SWAT, Das *et al.* (2021) [8] investigated how climate change affected hydro-climatological elements of Gomti River basin in India. Calibration, validation, and sensitivity analysis have all been used to assess model performance. R^2 and NSE values during the calibration and validation periods were 0.86, 0.87, and 0.79, 0.83, respectively. The most sensitive parameter, according to the sensitivity analysis, is SCS runoff curve number for antecedent moisture condition II (CN2), which is followed by saturated hydraulic conductivity (SOL_K), soil layer's available water capacity (SOL_AWC), etc.

It is evident from examining above reviews that model has a good applicability for predicting sediment. In sediment yield assessment experiments conducted worldwide under a variety of biological and environmental circumstances, SWAT model has demonstrated positive results. Therefore, the use of SWAT for soil loss prediction can be considered a positive development in hydrological studies, as soil is a valuable natural resource.

3.3 SWAT for impact assessment of land use and land cover (LULC) change

Land use and land cover is key to agricultural economics, offering multiple benefits. For decades, farmers have struggled with sustainable farming due to urbanization while ensuring food production without harming the future. However, social and economic growth depend on these factors. Urbanization and agriculture drive land cover change, which urgently requires conservation and sustainable management due to its impact on ecosystems, climate, and human well-being. Hydrological modeling addresses LULC challenges, with researchers using SWAT to study decadal LULC changes and their future implications.

There have been studies that used SWAT to examine how changes in land use land cover affect runoff and sediment yield. Anand *et al.* (2018) [2] assessed land use change on the hydrologic regimes of Ganga River basin, India with SWAT model. At various gauge sites spread along the Ganga River and its tributaries, the simulated streamflow was compared.

The primary cause of the rise in surface runoff and water yield has been urbanization. On the other hand, rising irrigation demands were the main cause of both the increasing ET and the water usage. This study can be a useful tool for measuring how hydrological components change in response to land use changes, particularly in basins that are rapidly becoming commercialized.

Sinha *et al.* (2018) [33] examined how historical and projected LULC changes affected monthly streamflow as well as sediment yield in Netravati river basin, India. LULC maps were created for six periods: 1972, 1979, 1991, 2000, 2012, and 2030, with the 2030 map forecasted under a normal growth assumption. Findings showed that from 1972 to 2030, grassland (11.17-4.41%), forest (53.04-27.03%), and bare land (1.09-0.16%) decreed, while agricultural (31.38-55.75%), urban (1.80-9.96%), and water bodies (1.48-2.66%) increased. According to the findings, the catchment area's runoff increased by 428.65 and 58.67 mm, respectively, and its sediment output increased by 348 t/km^2 and 43 t/km^2 between 1972 and 2030 as a result of LULC trends in urbanization and agricultural intensification.

Sinha *et al.* (2023) [34] investigated how surface runoff in Kadalundi river basin, Western Ghats was affected by changes in climate and LULC. For RCP (Representative Concentration Pathway) 4.5 and 8.5 emission scenarios, climate change scenarios for near (2011-2040), mid (2041-2070), and far (2071-2099) future time periods were obtained from five distinct general circulation models. The 2014 LULC was projected using the 1988 and 2000 LULC and verified with 2014 LULC. The 2030 LULC was projected using 2000 and 2014 LULC, and 2050 LULC was projected using 2014 and 2030 LULC. According to the findings, between 2000 and 2050, the mean annual surface runoff increased while the amount of forest and grassland decreased and the amount of agricultural and urban areas increased. In the near, mid, and distant future, mean annual surface runoff would decrease under both RCP 4.5 and RCP 8.5 for climate change scenarios that were evaluated, with RCP 8.5 indicating worse conditions than RCP 4.5. Surface runoff trended downward in the near and mid-term due to the combined effects of climate change and LULC. Additionally, the predicted results show that, in both RCP scenarios, surface runoff will be higher in the winter and summer, with a generally opposite tendency during the monsoon season.

With SWAT model, Waikhom *et al.* (2023) [40] investigated impact of LULC for upper Shetrunji River basin. SUFI-2 algorithm of SWAT-CUP was used to validate and calibrate model. With a three-year warm-up phase from 1997 to 1999, data from 2011 to 2020 were used for validation, while the data from 2000 to 2010 were used for calibration. ERDAS IMAGINE 2015 has been used to detect LULC changes through a supervised classification method. The simulated and observed streamflow data showed good agreement during model calibration (NSE = 0.74 and R^2 = 0.78) and validation (NSE = 0.70 and R^2 = 0.73). Agricultural, urban, and water body areas grew between 2000-2010 and 2010-2020, while forest areas increased in 2010 and decreased in 2020, according to LULC change detection. They came to the conclusion that the upper Shetrunji River basin's runoff was greatly impacted by the shift in LULC.

3.4 SWAT for climate change impact studies

Because of this, the greenhouse effect of the atmosphere is exacerbated, altering patterns of precipitation and snowfall, increasing average temperatures, and making extreme weather events like drought and floods more frequent. This put greater pressure on water supplies and is also having an impact on hydrology globally. Preventing climate change before it has an impact on Mother Earth's future has become imperative. The possible effects of anticipated changes in climate and water resource management can be demonstrated using hydrological model. There are numerous studies on the effects of climate change and interactions of SWAT models. Nevertheless, outcomes of these studies depend greatly on the present and the future scenarios.

Study has been conducted by Narsimlu *et al.* (2013) [21] to evaluate potential effects of climate change on Upper Sind River Basin's water supplies. For study, PRECIS-generated outputs from IMD, Pune, India, under IPCC A1B Scenarios for Indian circumstances, which correspond to baseline (1961-1990), midcentury (2021-2050), and end century (2071-2098) were used. According to model estimates, the average annual streamflow might rise by 16.4% by middle of century and by a substantial 93.5% by the end of the century. According to the findings, streamflow may increase significantly during the monsoon season but will fall during the non-monsoon season as a result of projected future climate change scenarios.

There is study undertaken by Uniyal *et al.* (2015) [38], they have assessed impact of climate change on water balance components (WBCs) of Upper Baitarani River basin, India using SWAT model. Twelve separate and twenty-eight combined area-specific climatic scenarios were considered. The analysis of model results for the 12 Independent Climatic Scenarios showed that altering the temperature from 1 to 5^0 C reduced surface runoff by 2.5 to 11%, while increasing rainfall by 2.5 to 15%, surface runoff increased by 6.67 to 43.42% from the baseline condition. When comparing the 28 Combined Scenarios to the baseline state, ET would rise from 4.05 to 11.88%, the groundwater recharge would change from -8.7 to 23.15%, and surface runoff would change from -4.55 to 37.53%.

Using the SWAT, Pandey *et al.* (2017) [24] assessed the effects of climate change on hydrology of the Armur watershed in Godavari River basin, India. WBCs were determined for future climate scenarios (2071-2100) and the baseline scenarios (1961-1990). Results showed that, in comparison to the base line scenario, increases in average annual temperature (+3.25^0 C), average annual rainfall (+28%), ET (28%) and water yield (49%) increased for future climate scenarios.

Another study in India, Padhiary *et al.* (2020) [23], used two different CMIP5 models (CNRM-CM5.0, GFDL-CM3.0) under two RCPs, i.e., 4.5 and 8.5 scenarios, to evaluate the effects of climate change in Anandapur watershed (Baitarani River basin). According to the study's findings, rain and temperature may gradually increase in the future when the monsoon shifts from mid-June to mid-May. Under both RCPs, the period 2046-2070 showed the highest average annual ET, whereas the period 2071-2095 saw the largest rise in average annual streamflow. As a result, groundwater recharging across the basin was considerably slower.

Kumari *et al.* (2024) [17] determined impact of changing LULC using RCP 8.5 Pathways climate scenario on the monthly streamflow in Subarnarekha basin, India. In this study, LULC modification caused a decrease in water bodies, an increase in built-up area, and a decrease in agricultural land, all of which contributed to higher surface flow. Additionally, under RCP8.5, there was an increase in the expected temperature and a decrease in yearly precipitation. Certain components of the water balance are slightly increasing, despite the fact that annual precipitation is decreasing. Water yield dropped by 13.33 mm and surface flow increased by 98.85 mm between 2013 and 2020. However, surface flow increased by 142.85 mm under the climate change scenario. Water production dropped by 21.88 mm, lateral flow dropped by 7.06 mm, and groundwater flow dropped by a further noteworthy 68.37%.

3.5 SWAT to identify erosion prone areas

The exact sites of sediment losses had to be determined because sedimentation has become a major issue that affects reservoir capacity and fertile soils for crop production. When the precise sites of soil erosions are known, management may be planned and actions can be taken to manage time and money effectively. Many researchers have utilized SWAT, a hydrological model, to identify places where soil or water erosion has occurred.

Sardar et al. (2014) [30] spotted the erosion-prone areas of Barakar Basin, Jharkhand. Model was calibrated and validated on monthly basis for flow to Maithon and Tilaiya Reservoirs for periods of 1997 to 1999 and 2000 to 2001, respectively. Furthermore, during the monsoon season of the same period, it was calibrated and validated for monthly runoff and sediment yield from two sub-watersheds (Banha and Karso) located inside the Barakar Basin. To lower the rate of sedimentation in reservoirs, subwatersheds were categorized into seven categories of priority and treated one after the other. The rate of sedimentation decreased as a result of the management plan's adaptation. For Tilaiya and Maithon Reservoirs, the sedimentation rate dropped from the current rates of 0.76 and 4.59 mm^3/y to 0.56 and 1.41 mm^3/y, respectively. Additionally, Tilaiya and Maithon Reservoirs' lifespans were extended by 29 and 166 years, respectively. Therefore, by lowering the reservoir sedimentation rate, SWAT can be used to identify crucial sub-watersheds and create management plans to control erosion from critical locations.

Kumar and Mishra (2015) [15] identified specific erosion prone areas within the watershed for Damodar catchment, India at watershed and hydrological response unit (HRU) level with SWAT model. According to the HRU level analysis, the combination of sandy loam soil with wetland and agricultural has put 67.51% of the study area under critical erosion circumstances. The results of the study also demonstrate that, within the watershed with varying topography, erosion is fairly sensitive to land use and soil type.

In order to forecast soil erosion and sediment transport to the reservoir, Dutta and Sen (2017) [9] employed SWAT model for Mahanadi watershed up to Hirakud (Chhattisgarh and Odisha). According to the study, over 34% of the catchment's total area is in high or above soil erosion zones, which are characterized by a mix of coarse loamy soil, agricultural land use, and land cover conditions. As a result, the model may pinpoint important regions of the watershed that are prone to erosion at the sub-watershed scale, assisting hydrologists in implementing cost-effective management techniques.

Kumar and Mishra (2015) [15] identified critical watersheds that are susceptible to soil erosion. They demonstrated that 406 watersheds that were defined using the computer software model within the catchment could be successfully prioritized utilizing the model. The boundaries of 175 watersheds during the delineation procedure precisely matched the watersheds that Damodar Valley Corporation had physically drawn. 157 of these 175 watersheds had erosion classes that precisely matched the one that was manually specified. Eight watersheds displayed total mismatch, while ten of the remaining 18 watersheds had a priority that was either one class higher or lower. They concluded that hydrological model would be useful for setting priorities for resource management tactics.

Shivhare *et al.* (2018) [32] applied SWAT model for Ganga catchment (15,621.612 km^2), Uttar Pradesh. The watershed was divided into 46 sub-watersheds, and HRUs were created using LULC and soil maps. Five parameters were found to be sensitive for modeling this watershed after SUFI-2 calibration. These parameters included the effective channel hydraulic conductivity (CH_K2), USLE support parameter (USLE_P), Manning's n value for the main channel (CH_N2), the surface runoff lag time (SURLAG), and the available water capacity of the soil layer (SOL_AWC). Additionally, sub-watershed forty (SW#40) had the highest runoff, whereas SW#36, which was consist of bare land, had the highest sediment yield of 50 tons/ha. The basin's average evapotranspiration was 411.55 mm. They came to the conclusion that future research into the effects of soil erosion, LULC, and global climate change can be facilitated by using a calibrated model.

3.6 SWAT for estimation of water balance components (WBCs)

Study was performed in Mahanadi River basin in India by Singh *et al.* (2020) [35] to predict WBCs and streamflow for the Ib River watershed. The results showed that when comparing calibration and validation, calibration's response was better; the R^2, NSE, and PBIAS were 0.77, 0.75 and -19.1, respectively. According to this study, ET decreased between 26 and 50 percent of the rainfall. Due to the prevalence of tile drainage, the southern region had stronger lateral flow, lower groundwater, and greater spatial variability in surface runoff. The behavior of hydrological components on the sparse rain network will be better understood due to this study.

Arumugam *et al.* (2025) [4] evaluated hydrological behavioral changes of the Noyyal watershed, Tamil Nadu, India. 15 years of data on variables like temperature, relative humidity, wind speed, rainfall, and sun radiation were stimulated with SWAT. For sensitivity analysis, calibration, and validation, SUFI-2 was used. Monthly calibrations and validations of sediment output and streamflow were conducted in this investigation. For validation, four-year period from 2011 to 2014, and for calibration a 12-year period from 2003 to 2014 were selected. The statistical indices (PBIAS, NSE, PSR, and R^2) demonstrate that model simulates hydrology "excellently." SUFI-2 was found to be quite user-friendly and acceptable when compared to the other automatic calibrating methods.

The WBCs for Chittar catchment in Tamilnadu, India, were estimated by Pandi *et al.* in 2023. Eleven sub-catchments were created from the catchment. The model was developed using the ten-year interval LULC (2001 and 2011), the twenty-year daily meteorological data (2001-2020), and time-invariant soil and slope data. Model was calibrated and assessed using monthly river gauge discharges. Pre-calibration (2001-2003) and post-calibration (2004-2010) are two phases of the model calibration process. Using unseen river gauge discharging data (i.e., 2011-2015), the model's performance was assessed. Pre-calibration, post-calibration, and validation had R^2 of 0.75, 0.94, and 0.81, respectively. Between 2001 and 2020, they simulated five WBCs at the sub-catchment level: surface runoff, lateral flow, percolation, real evapotranspiration, and soil water. Due to the northeast monsoon's failure, a protracted drought was seen in all 11 sub-catchments from 2016 to 2018.

By examining separate and combined effects of and LULC changes and climate change in Pamba River basin, Western Ghats, India, Sharma *et al.* (2024) [31] evaluated the changes in historical, present, and future WBCs. An ensemble of five GCM scenarios with RCPs 4.5 and 8.5 was taken into consideration in order to examine the near (2021-2040), mid (2041-2070), and long (2071-2099) future impacts of changing climate and LULC on WBCs. Using the Land Change Modeler (LCM), future LULCs for 2030, 2050, 2075, and 2100 were created while taking typical LULC expansion into account. The data show that, from 1988 to 2100, the effects of LULC alteration resulted in a drop in ET while increasing water production and surface runoff. The implications of climate change show that under both RCP scenarios, water yield, surface runoff, and ET will decrease in future. Future combined influences on water yield, surface runoff, and ET followed a similar trajectory to the trend of climate change. The results demonstrate that, due to changes in temperature and precipitation under RCP 4.5 and 8.5 emission scenarios, climate change will significantly affect WBCs in the PRB.

Kausher *et al.* (2024) [14] simulated the hydrologic behavior and streamflow of the Mahan River catchment region over several decades, taking into account the effects of six underground and opencast mines. Compared to sub-watersheds in non-mining areas (159.40 Metric Ton/ha), sediment yield in mining area sub-watersheds (SW20, SW26, SW28, SW31, and SW38) was lower (61.41 Metric Ton/ha). At 531.2 mm, evapotranspiration made up 39% of the 1365.3 mm of precipitation that fell each year. With surface runoff of 351.89 mm, return flow of 402.21 mm, lateral flow of 21.47 mm, and 58.86 mm of percolation into confined and unconfined aquifers for soil and groundwater storage, the total discharge was estimated to be 775.57 mm. The model performed well during the simulation, and the results showed that mines play a significant influence in changing the watershed's hydrological regime, which has moderate evapotranspiration and low recharge.

Using SWAT, Kumar *et al.* (2025) [18] calibrated and validated water balance of Kosi River Basin. Model was developed between 2000 and 2013 using monthly streamflow data and daily gridded rainfall data from IMD, Pune. With NSE and R^2 statistical values exceeding 0.70 and 0.72 during calibration and 0.67 and 0.70 during validation, model demonstrated strong performance. The spatiotemporal variation of the water budget component was estimated across the study area. The results revealed that around 35% of the rainfall collected was lost due to ET. The regional variability chart shows that ET loss was greater in the northwest region due to abundant vegetation. This research will help us better understand how water budget components respond to a sparse rainguage network in Uttarakhand's hilly terrain.

Conclusions

This research addressed the application of SWAT model for runoff and sediment yield simulation, identification of erosion prone areas as well as the prediction of LULC change and climate change impacts on natural resources management in India. The SWAT model is an integrated, widely recognized tool used for multidisciplinary research at the regional level under a variety of physiographic and meteorological conditions. The model can examine both short-term and long-term impacts in small to large scale basin. SWAT can be used for forecasting the climate and topographical conditions for any catchment with reliable information or identical data for ungauged areas. It is concluded that SWAT model is a useful tool for analyzing river basins and creating long-term plans to mitigate impacts of land use changes and climate change throughout the world.

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