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Integrated Hydrological Modeling of the Godavari River Basin in Maharashtra Using the SWAT Model: Streamflow Simulation and Analysis

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Abstract

Hydrological modeling plays a crucial role in efficiently managing water resources and understanding the hydrologic behavior of watersheds. This study aims to simulate daily streamflow in the Godavari River Basin in Maharashtra using the Soil and Water Assessment Tool (SWAT). SWAT is a process-based hydrological model used to predict water balance components, sediment levels, and nutrient contamination. In this research, we used integrated remote sensing and GIS data, including Digital Elevation Models (DEM), land use and land cover (LULC) maps, soil maps, and observed precipitation and temperature data, as input for developing the SWAT model to assess surface runoff in this large river basin. The Godavari River Basin under study was divided into 25 sub-basins, comprising 151 hydrological response units categorized by unique land cover, soil, and slope characteristics using the SWAT model. The model was calibrated and validated against observed runoff data for two time periods: 2003-2006 and 2007-2010 respectively. Model performance was assessed using the Nash-Sutcliffe efficiency (NSE) and the coefficient of determination (R2). The results show the effectiveness of the SWAT2012 model, with R2 value of 0.84 during calibration and 0.86 during validation. NSE values also ranged from 0.84 during calibration to 0.85 during validation. These findings enhance our understanding of surface runoff dynamics in the Godavari River Basin under study and highlight the suitability of the SWAT model for this region.

Keywords

Soil and Water Assessment Tool (SWAT), Streamflow, Hydrological Modeling, Rainfall, Runoff

1. Introduction

Water is an essential resource required for human activities, but its availability is a growing concern due to the increasing global population, water pollution, and drastic climate changes. These challenges demand immediate attention from the current generation to ensure sustainability [1]. To assess water availability, understanding the water balance of a region becomes crucial. The estimation of key hydrological processes related to water resource management relies on the water balance equation, which is greatly influenced by the physical characteristics of the watershed, including its morphology, land use, and soil composition. Given the complexity of hydrological processes, watershed models are widely employed to grasp them effectively [2]. Hydrological modeling is a vital tool for researchers and engineers involved in water resources management. The Soil and Water Assessment Tool (SWAT) is a popular watershed model used for evaluating streamflow, sediment transport, and nutrient movement. Developed by the Agricultural Research Services of USDA, SWAT is widely used in India and has been applied successfully in various Indian basins to simulate runoff and sediment yield, especially in regions where heavy rainfall during the monsoon season significantly affects river flow (SWAT operates on a daily or monthly time scale and has been utilized to assess the impact of climate change and human activities on streamflow, agricultural chemicals, and sediment yields in large river basins [3]. The Soil and Water Assessment Tool (SWAT) model is a physically based, semi-distributed hydrological model that operates on a daily time scale. Its semi-distributed approach allows for the simulation of hydrology, sediment, and nutrient movements, enabling the assessment of watershed hydrological behavior [4]. Extensive research on SWAT applications has demonstrated its utility in simulating hydrological systems with varying data. SWAT is widely recognized as a leading hydrological model used to address global hydrological and environmental challenges. This model, based on physical principles, offers a continuous-time, semi-distributed approach, and is designed to assess water resources and predict the effects of land use changes and land management practices on soil erosion, sedimentation, and non-point source pollution in watersheds or large river basins [5]. The original purpose of the SWAT (Soil and Water Assessment Tool) model was to forecast discharge from ungauged basins. The hydrological elements of the SWAT model [6] are determined by the water balance Equation (1), which is as follows:

$$Swt = Swo + \sum \left(Rday - Qsurf - Ea - Wseep - Qgw \right) ti = 1 \quad (1)$$

where: *Swt* is the final soil water content (mm); *Swo* is the initial soil water content on day 1 (mm); *Rday* is the amount of precipitation on day 1 (mm); *Qsurf* is the amount of surface runoff on day 1 (mm); *Ea* is the amount of evapotranspiration (*ET*) on day 1 (mm); *Wseep* is the amount of water entering the vadose zone from the soil profile on day 1 (mm); *Qgw* is the amount of return flow on day 1 (mm). SWAT is comprehensive; hence it has also shown to be quite flexible in solving a variety of water resource issues [7]. Streamflow is an essential metric for determining water availability at the river basin level. Hydrological models, including the Soil and Water Assessment Tool (SWAT), have been extensively used over the past two decades to assess water availability and predict extreme events. SWAT, for instance, incorporates Digital Elevation Models, land use maps, soil maps, and meteorological parameters to generate runoff at the basin scale. This model employs two fundamental equations, namely the Soil Conservation Services-Curve Number (SCS-CN) method for runoff estimation. [8]. The objective of our study is to apply the QSWAT model for hydrological modeling in the Godavari River basin in Maharashtra on a large scale. The QSWAT model will be used to predict streamflow values. We employed the SWAT CUP SUFI 2 algorithm for calibration and validation of simulated streamflow and conduct sensitivity analysis of parameters to determine the most influential model parameters affecting water yield.

2. Study Area

The Godavari River, second in length only to the Ganga in India, originates from Trambakeshwar in Nashik, Maharashtra. It courses eastward until it reaches the Nanded District within the state of Maharashtra. The study region shown in Figure 1 encompasses the upper and middle sections of the Godavari River, spanning from Trambakeshwar in Nashik district to Vishnupuri in Nanded district, Maharashtra. This area encompasses a stretch of approximately 350 kilometers and has a basin area of approximately 51381.75 square kilometers for the research study.

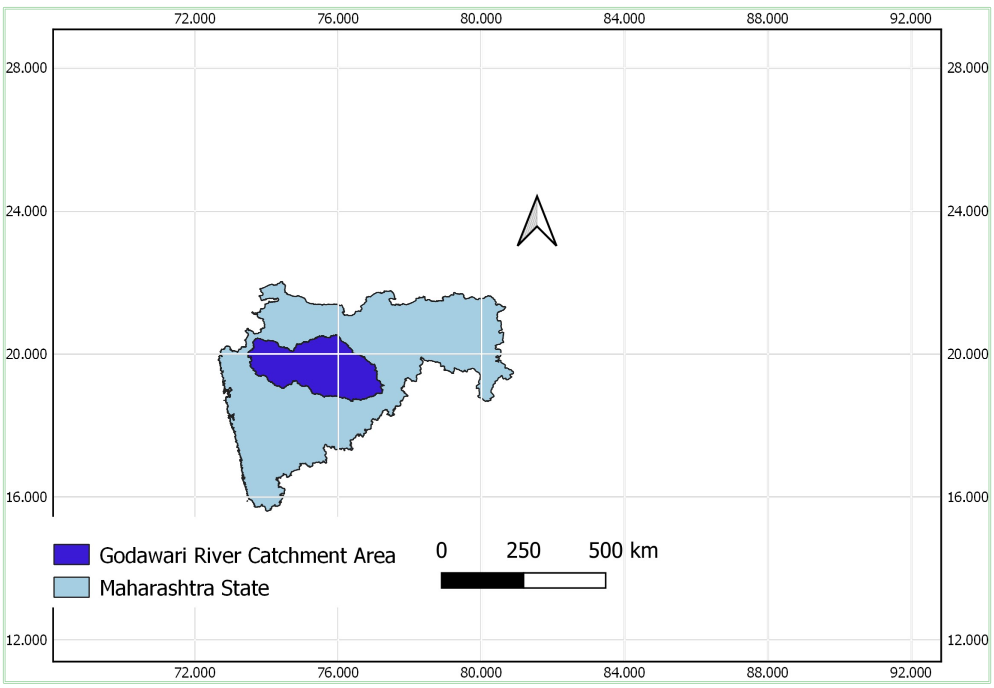

Figure 1. Godavari river basin map.

3. Input Data Set

3.1. Weather Data

The meteorological data used in this study includes daily recorded data series of stream flow, solar radiation, relative humidity, wind speed, maximum and minimum temperatures, and precipitation (pcp). The Global Weather Data for SWAT, accessible at https://www.uoguelph.ca/watershed/w3s/, provided the daily data for the research area.

3.2. Elevation Data

Figure 2 represents the DEM for study area. In this research, we utilized a Digital Elevation Model (DEM) derived from the Shuttle Radar Topography Mission, which was obtained from https://earthexplorer.usgs.gov with a resolution of 30 meters.

3.3. Soil Data

The soil information was sourced from the National Bureau of Soil Survey and Land Use Planning—Indian Council of Agricultural Research (NBSS). Figure 3 represents the soil map for the Godavari River basin under study. In the study area, the soil has been categorized into seven classes, which include water bodies, silty clay loam soil, loamy sand, clayey soil, loam soil, clay loam soil, and sandy loam soil. To incorporate this soil data into the SWAT reference database (QSWATRef2012.mdb), users are required to import the soil data for each of the map categories. A Soil Lookup table is employed to reclassify the soil map categories.

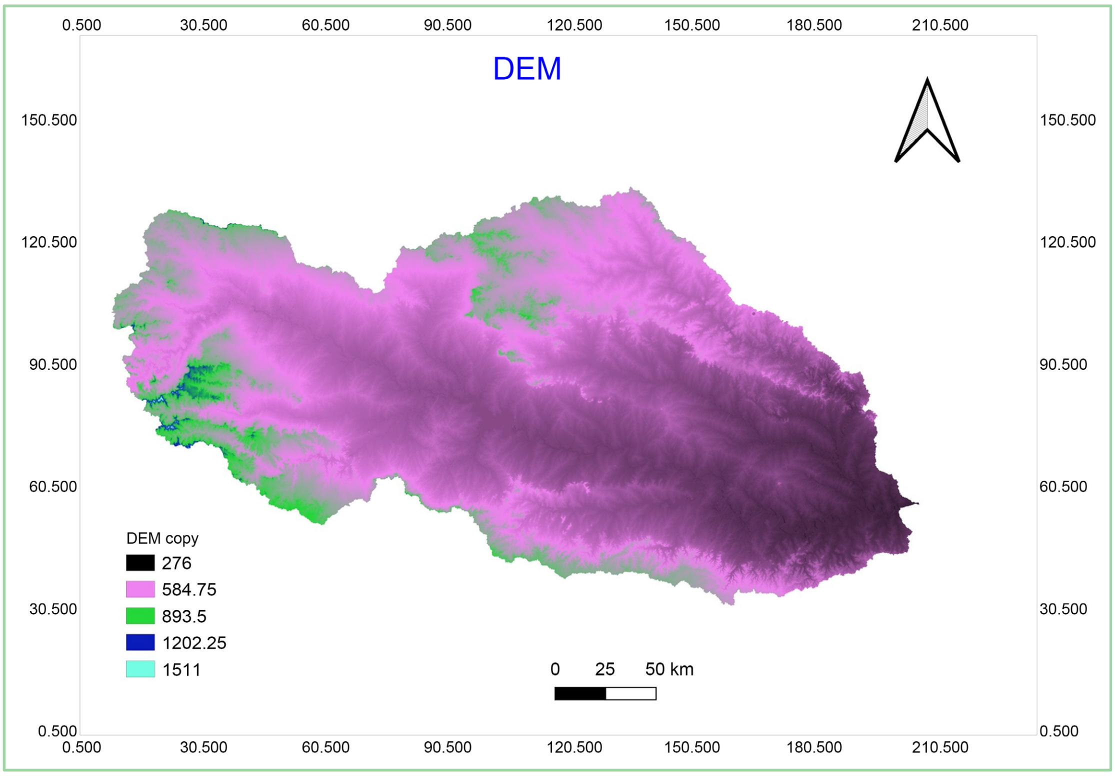

Figure 2. Digital elevation model of Godavari river basin under study.

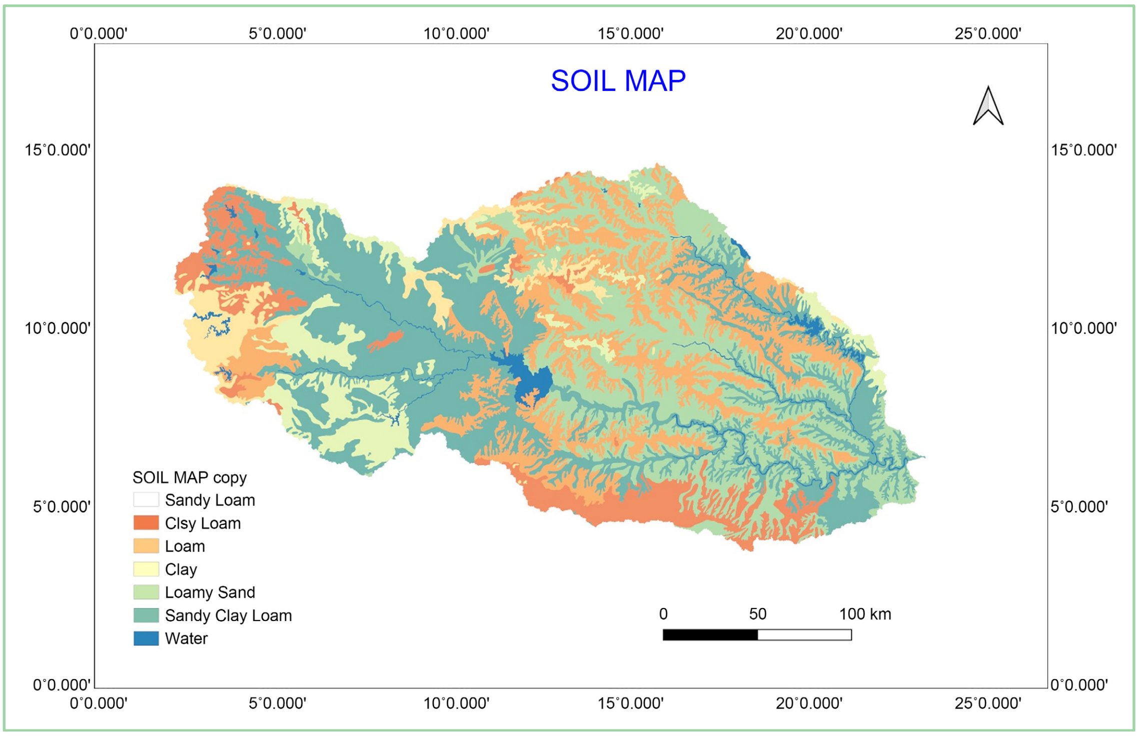

Figure 3. Soil map of Godavari river basin under study.

3.4. Land Use/Land Cover Map

LANDSAT 5 (TM) imagery was employed for the land use/land cover (LU/LC) classification within the study region. The LANDSAT 5 data has a spatial resolution of 30 meters and was acquired from the http://earthexplorer.usgs.gov/ website. To create the land use and land cover map, a supervised classification technique was utilized. The land use categories outlined in the map will require reclassification into SWAT land cover and plant types using a Land Use Lookup table. Figure 4 represents the land use land cover map for the study area showing the seven classes.

4. Methodology

Based on measured rainfall and maximum and minimum temperatures, we used the SWAT hydrological model in this study to estimate surface runoff. For the purpose of modelling runoff dynamics, the model required the inputs of a DEM (Digital Elevation Model), a Land Use/Land Cover (LULC) map, and a soil map. Figure 5 shows a flowchart that details how the surface runoff is calculated for Godavari River basin under study. DEM for the Godavari basin under study was retrieved from30-meter-resolution Shuttle Radar Topography Mission (SRTM) tiles from Earth Explorer. These tiles were then imported into QGIS, where they were combined to produce a mosaic file and reprojected to WGS 84 UTM ZONE 43. This mosaic file was clipped using a shapefile reflecting the watershed to define the Godavari basin under study. Utilizing a shapefile of the watershed boundary in the same projection system, tiles were acquired from Earth Explorer and clipped with the Godavari basin image to create the Land Use/Land Cover map. The thematic maps from NRSC, Nagpur, which depicted about 32 distinct soil types in the Godavari basin, were combined to create the soil map. Each type of soil was given its own shapefile, which were then combined using the mapping units given in (NBSS&LUP) [9].

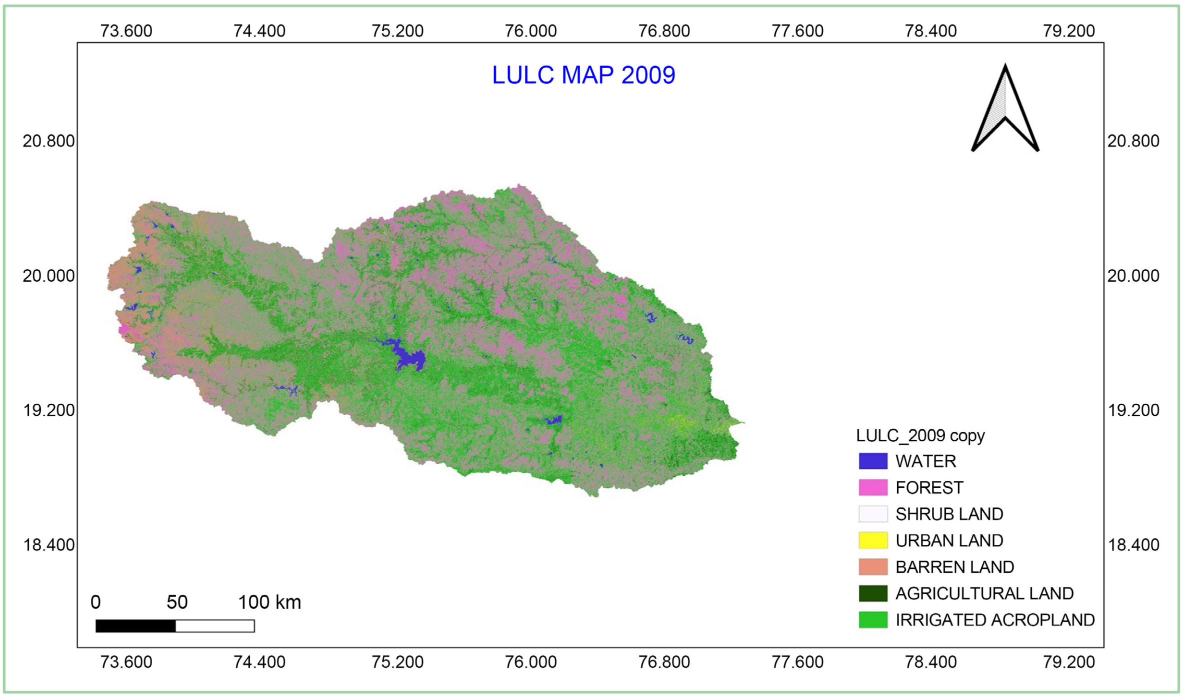

Figure 4. Land use and land cover map of Godavari river basin under study.

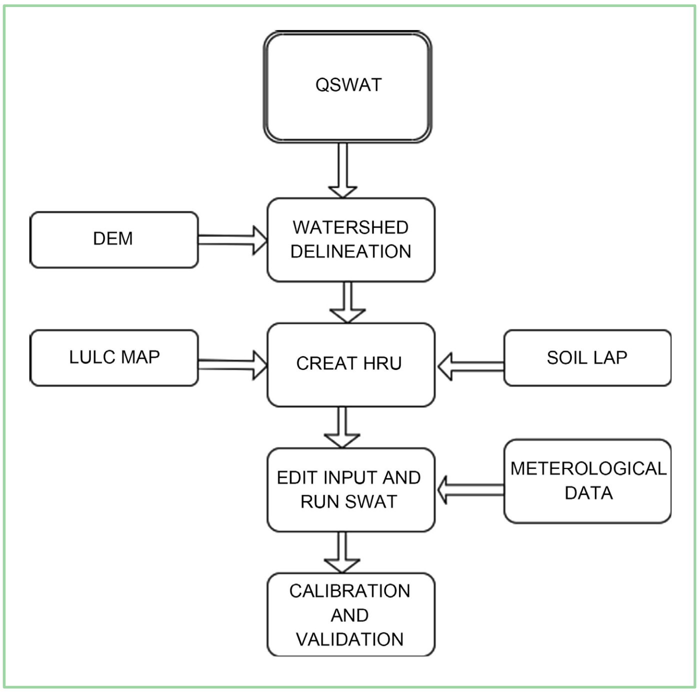

Figure 5. Framework for streamflow simulation by SWAT model.

With the input datasets prepared, the SWAT model was executed following the subsequent steps.

Watershed Delineation:

The DEM was introduced as an input file for the SWAT run, which was the first stage. The watershed's slope and contour lines are used by the model to determine the direction of flow and accumulation. The model created a stream network that eventually converged into a large reach based on this data. The basin is divided into sub-basins by the stream network, which also designates the outlet.

Analysis of the Hydrological Response Unit (HRU): Overlaying the maps of soil, slope, and land use/cover was part of the HRU analysis. After this overlay was finished, HRU reports were produced using the distinct combinations of soils, land use, and land cover.

Write Input Tables: In order to execute the SWAT simulation, weather generator data and meteorological input data (temperature and precipitation) were formatted into specific tables at this step.

SWAT Run: The SWAT model was run once the input tables were prepared and the simulation period was set. Data on daily stream flow and the water basin's water balance components were included in the simulation's output.

Calibration using SWAT-CUP: The final stage of the process involved model calibration using the SWAT-CUP SUFI 2 algorithm.

5. Result and Discussion

5.1. SWAT Model

The study employed the SWAT model to gain valuable insights into the land use, soil characteristics, and hydrological behavior within the period spanning from January 2001 to December 2010. The Land Use/Land Cover map, comprising was classified into 7 classes (**Figure 4**). This analysis revealed that Croplands dominated the landscape, covering a vast expanse of 68.45% of the total land cover. This classification provided a clearer picture of the land use distribution in the study area, highlighting the significant role of croplands in the basin. Furthermore, the soil map underwent classification into 7 classes based on Mapping units (**Figure 3**). Additionally, the model incorporated 5 different slope categories (**Figure 2**). This comprehensive classification of soil types and variations in slope allowed for a more detailed assessment of the terrain and its hydrological implications. Based on the HRU analysis reports, the SWAT model efficiently generated 151 Hydrological Response Units (HRUs) and identified 25 subbasins within the Godavari basin under study. These HRUs and subbasins are crucial components for comprehending the hydrological processes and interactions within the basin. The SWAT simulation was conducted on a daily basis over a 10-year period. The average monthly monsoon precipitation was calculated to be 915.6 mm, while the average monthly surface runoff was estimated at 435.78 mm. These findings are pivotal for assessing water availability and potential runoff in the basin. One critical parameter analyzed in the SWAT output is the average curve number, which was determined to be 81.42. A higher curve number suggests a greater potential for surface runoff. The relatively high curve number observed implies that the Godavari basin may experience increased surface runoff due to its land use characteristics and soil types [2]. The results of applying the SWAT model unveiled valuable information regarding land use distribution, soil types, and hydrological dynamics within the Godavari basin. The dominance of croplands, along with specific soil types and slope variations, plays pivotal roles in shaping the basin's hydrological behavior. The successful implementation of the SWAT simulation and the insights derived from its outputs underscore the importance of such modeling approaches in supporting water resource management and planning in the study area.

5.2. Calibration Procedure and Sensitivity Analysis Using SWAT CUP SUFI-2

The SUFI-2 approach has been used for calibration, validation, and sensitivity analysis to get an ideal range of parameters since it requires less simulations than other techniques including Bayesian inference, parameter solution (ParaSol), and generalized likelihood uncertainty estimation (GLUE). The scope of each parameter was defined at the start of the procedure. The Latin hypercube approach was used to produce several combinations of sensitive parameters during calibration. These combinations were then used to run the model, and the outcomes were contrasted with the data that was observed. This procedure persisted until the ideal objective function was reached. The SUFI-2 algorithm computed a p-factor and r-factor in order to evaluate measurement uncertainty. The cumulative distribution of an output variable acquired via Latin hypercube sampling yields the p-factor, which is the percentage of measured data lying inside the 95 percent prediction uncertainty (95PPU) [10]. On the other hand, the r-factor represents the 95PPU's average thickness divided by the measurement standard deviation. To find the ideal parameter range, the main objective of the SUFI-2 algorithm is to maximize the p-factor and minimize the r-factor. A t-test was used to assess the sensitivity of the parameters; a higher t-test value denotes a more sensitive parameter, and vice versa [11]. In order to determine the precise parameter range, our study required 1000 parameter variations for every iteration. To find the ideal objective function and define parameter ranges, three iterations were carried out. The model was calibrated using the 15 most sensitive parameters, as well as their fitted values and upper and lower bounds.

We computed R^2, p-factor, r-factor, and Nash-Sutcliffe efficiency (NSE) for performance evaluation by contrasting the monthly flow observed during the calibration and validation periods with the simulated flow. R2, NSE, p-factor, and r-factor had calibration values of 0.84, 0.84, 0.71, and 0.46, respectively, and validation values of 0.86, 0.85, 0.73, and 0.54, respectively. These findings suggest that the model operated successfully in the research domain. Significantly, R^2 and NSE values increased during the validation phase in comparison to the calibration, presumably because of more precise observed data and suitable land use-related factors employed during validation.

Table 1. Water balance of the study area for the observed period (2001-2010).

Hydrological component	Amount (mm)
Precipitation	915.6
Surface runoff	435.18
Lateral flow	10.86
Groundwater (shallow aquifer)	390.03
Revap from shallow aquifer	1.8
Evapotranspiration	75.8

5.3. Water Balance for the Observed Period (2001-2010)

The mean annual water balance simulation data for the years 2001-2010 are shown in Table 1. There was 915.6 mm of total precipitation noted. 75.8 mm of this were lost as a result of ET (Evapotranspiration). A total of 435.18 mm and 10.86 mm of precipitation was contributed by surface runoff and lateral flow, respectively. Part of the precipitation seeps through and becomes stored in the earth. It was estimated that the mean annual water production for the research region, which could be used for irrigation and drinking, was 832.53 mm of total precipitation. The monsoon season accounted for around 70% of the average yearly water yield, which is noteworthy.

6. Conclusion

The SWAT model has proven to be successful in yielding favorable outcomes for the research region within the Godavari basin. The substitution of agriculture with eucalyptus in the basin led to a decline in both the average and minimum reference streamflow. This study marks the first comprehensive assessment of the hydrological components of the Godavari River Basin, spanning from its origin in Nashik to Nanded, employing the SWAT model for simulating streamflow and estimating water balance elements. The model's performance was evaluated using statistical indicators (NSE, R2), with NSE values of 0.84 and 0.85, and R2 values of 0.84 and 0.86 for calibration and validation, respectively. These results indicate a reasonably strong agreement between observed and simulated streamflow data on a monthly time scale. Temporal and spatial variability within the Godavari River Basin was analyzed, revealing that 15% - 30% of rainfall was lost through evapotranspiration, with minimal losses through lateral flow, 8% - 12% through groundwater flow, and 13% - 22% through percolation. Spatially, surface runoff was higher in the Upper Godavari Basin region due to consistent rainfall and hilly terrain, while the Middle Godavari Basin region experienced lower runoff due to irregular rainfall patterns. The study's findings provide a quantitative approach to understanding the water balance components in the basin, aiding water resource management and informing policymakers on effective watershed management. However, it is important to note a limitation in the study, which is the reliance on a single stream gauge that may not accurately represent spatially distributed simulated model responses. The future scope of the study involves incorporating projected climate data for future climate scenarios and land use/land cover (LULC) changes to estimate the future dynamics of water balance components.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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