SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V13I8P103

Volume 13 Issue 8, 51-65, August 2026

Original Article

Simulation of Surface Runoff for Khadakwasla-Dasave Watershed, Pune, India Using SWAT Model

Shilpa Motegaonkar[1], Ajay Chavadekar[2], Harshal Rasal[3]

[1]*Department of Civil Engineering, Pimpri Chinchwad College of Engineering, Pune, Maharashtra, India.*
[2]*Department of Civil Engineering, Dr. D. Y. Patil Institute of Technology, Pune, Maharashtra, India.*
[3]*Hydrologic and Hydraulic Modeling (Water), AECOM India Global Services Private Ltd, Gurgaon, Haryana, India.*

[1]*Corresponding Author : shilpa.motegaonkar@pccoepune.org*

Received: 30 April 2026 Revised: 25 June 2026 Accepted: 14 July 2026 Published: 31 August 2026

Abstract *- Accurate prediction of surface runoff is critical for watershed management, flood risk assessment and water resource planning. This study has applied the Soil and Water Assessment Tool (SWAT) model using Geographic Information Systems to predict monthly surface runoff in the Khadakwasla - Dasave watershed, Pune district, Maharashtra, India. The watershed covers a total area of 265,680 hectares with an average elevation of 650 meters mean sea level. Soils are mainly clay and clay-loam, and about 74% of the region is used for cultivation. For model parameterization, we used 30 meter digital terrain models derived from Shuttle Radar Topography Mission (SRTM), land use/land cover, soil properties, and weather data from 2000 to 2013 (the first two years were used for model warming-up). The years 2002-2009 were used for model parameterization, while 2010-2013 were used for model validation. The Sequential Uncertainty Fitting (SUFI-2) algorithm in the SWAT-CUP software was used to calibrate model parameters. Lacking streamflow data, observed runoff was calculated using the Soil Conservation Service Curve Number method, with a composite curve number of 81.47, based on Antecedent Moisture Condition II and Hydrological Soil Group C, and an initial abstraction ratio of 0.1. After calibrating for 22 iterations, statistical fit measures suggest high model accuracy: Coefficient of Determination (R^2) value of 0.94 and Nash-Sutcliffe Efficiency (NSE) value of 0.74 for calibration and 0.96 and 0.62 for validation, respectively. The watershed was discretised into 19 sub-basins and 398 Hydrological Response Units. The average monthly runoff simulated was 36.65 millimeters during calibration and 48.02 millimeters during validation. The results show that SWAT–SUFI-2 modeling approach provides a scientifically sound and implementable methodology for hydrologic modeling in a semi-arid Indian watershed.*

Keywords *- SWAT model, Surface runoff, SCS-CN method, SWAT-CUP, SUFI-2.*

1. Introduction

Increasing urbanisation, agricultural water requirements, and climate change create a growing global need for water resources. In India, rising population and the variable nature of the monsoon have made watershed-level water resource management a national priority [1]. Watershed is a basic hydrologic unit that receives precipitation over a drainage basin and concentrates the flow at a single outlet [2]. Surface runoff (that component of rainfall that runs off land into stream channels) is the primary process that drives the generation of floods, soil erosion and groundwater recharge.

As such, runoff estimation is crucial for reservoir management, drought monitoring, irrigation water resources, and urban flood risk assessment [3]. Conventional runoff estimation methods, such as the Rational Method and the SCS Curve Number, although simple to compute, do not to consider spatial variability in land cover, soil properties, and topography across large watersheds, as investigated by Zelelew [4].

Spatially distributed process-based models offer more physically-based alternatives for runoff simulation. The Soil and Water Assessment Tool (SWAT), developed by Dr. Jeff Arnold at the United States Department of Agriculture Agricultural Research Service (USDA-ARS), has been internationally validated and applied [5]. Jayakrishnan et al. [6] have studied SWAT models at the sub-basin scale, including hydrologic processes such as water, vegetation, sediment, nutrient, and agrochemical processes. It uses digital elevation models, soil databases, land use maps, and daily weather in a Geographic Information System.

The Khadakwasla-Dasave watershed (Central Ground Water Board sub-watersheds BHMU005, BHMU006 and BHMU013) is a hydrologically important watershed supplying drinking water to Pune, India's ninth most populous metropolitan area, and a major industrial and information technology hub on the Deccan plateau at an altitude of 560 meters (m) [7]. This watershed, comprising 265,680 hectares across Maval, Khed, and Haveli administrative divisions, has five major dams (Temghar, Khadakwasla, Panshet, Pavana and Mulshi) and is used for both water supply to urban areas and agriculture, as investigated by Umrikar [8].

SWAT has been extensively applied for runoff simulation in various Indian watersheds with contrasting climatic, topographic and land use settings. The following critical review of literature shows key studies which guided the current research. Malunjkar et al. [10] used SWAT to model the watershed of the Mahesh-gad (Maharashtra) and obtained Nash-Sutcliffe efficiencies of 0.62 (calibration) and 0.74 (validation) with coefficients of determination (R^2) of 0.98 and 0.95, respectively, validating the model's use in clay-rich Deccan soils, conditions identical to those encountered in the current study.

Swami and Kulkarni [11] modelled runoff and sediment yield in the Kaneri watershed (Western Maharashtra) using SWAT with the ArcGIS 10.1 / ArcSWAT 2012 interface. The monthly correlation coefficient R^2 values0.849 for calibration period during the period of 1979-2000 and R^2 as 0.801 for the validation period during years 2001-2013. This established the model's long-term reliability under diverse hydrologic conditions comparable to those faced in the Khadakwasla-Dasave basin.

Nilawar and Waikar [12] discussed using SRTM DEMs and SWAT to delineation. This finding identified an average annual surface runoff of 79.67mm and validated streamflow predictions using root mean square error and coefficient of determination metrics over a 30-year simulation period, which guided the data collection for this study. Jain et al. [13] explored SWAT for a Himalayan watershed and reported monthly R^2 of 0.90 (calibration) and 0.62 (validation). They highlighted the water balance equation as the basis for runoff partitioning in SWAT's computational engine. Manaswi and Thawait [14] employed SWAT-CUP with the SUFI-2 technique for the Karam River Basin in Madhya Pradesh. Their sensitivity analysis identified curve number (CN2), baseflow alpha factor (ALPHA_BF), groundwater delay time (GW_DELAY), and threshold depth for groundwater return flow (GWQMN) as the four most influential parameters, findings that align closely with the sensitivity analysis results obtained in this study. Himanshu et al. [15] calibrated SWAT for the Ken River Basin of Central India, achieving a simulation of 0.946 and R^2 of 0.959 for monthly calibration and validation.

Bansode and Patil [16] have used the SCS Curve Number method to estimate runoff in Aurangabad district and have calculated a composite CN of 74.75 for Hydrological Soil Group C with a 10-year runoff range of 135-707 mm. This justified the approach of adopting SCS-CN runoff as the calibration target, as observed runoff gauging was unavailable. Crucially, the Khadakwasla-Dasave watershed is not currently equipped with sub-basin level runoff gauging monitoring infrastructure and therefore required model-based calibration targets. The SWAT-CUP approach, coupled with parallel uncertainty analysis, therefore offered the procedural framework adopted in the present study. Abbaspour [25] and Hosseini et al. [26] calibrated the uncertainty associated with SWAT-CUP.

Recent developments in SWAT model applications have also shown the application of the model in diverse climatic and geographic conditions. Impact of climate change on the Himalayan river basin was assessed by Bhatta et al. [27], Gassman et al. [29] thoroughly reviewed the global applications of SWAT, identifying successful applications in more than 250 published papers covering a range of conditions from tropical to arctic climates. Hydrological modelling response under climate change conditions with the help of SWAT was studied by Shiferaw [28] and Kallon et al [32] provided a theoretical documentation of SWAT's hydrology processes, laying the theoretical groundwork for water balance, soil moisture content, and surface-groundwater interactions.

Within India, Tripathi et al. [30] showcased SWAT's potential for watershed management in agricultural settings in the Nagwan watershed, Madhya Pradesh, and the need for sensitivity analysis to ensure model accuracy. Nair and Mirajkar [31] used SWAT for evaluating climate change impacts on the Vaigai River basin in Tamil Nadu in order to demonstrate the model's capacity for future projections under a changing climate.

Most recently, Kallon et al. [32] investigated the integration of SWAT and MODFLOW for better groundwater representation in hard-rock aquifers, as found in the Deccan plateau, providing valuable insights for this study's geological context. This study aims to: (i) develop and parameterise a SWAT model for the Khadakwasla-Dasave watershed; (ii) identify the most sensitive hydrological parameters controlling runoff generation; (iii) calibrate and validate the model using SCS-CN-derived observed runoff through SWAT-CUP with SUFI-2 uncertainty analysis; and (iv) evaluate model performance using R^2 and NSE statistical metrics in accordance with the criteria established by Moriasi et al. [9].

2. Study Area

The Khadakwasla–Dasave watershed is located in Pune district, Maharashtra, India, between latitudes 18.29°N – 18.74°N and longitudes 73.34°E – 74.33°E. The watershed drains through the Mula-Mutha river system, which ultimately joins the Bhima River and the Krishna River, discharging into the Bay of Bengal. Figure 1 shows the study area: Khadakwasla-Dasave Watershed location in the CGWB Watershed Map of Pune District.

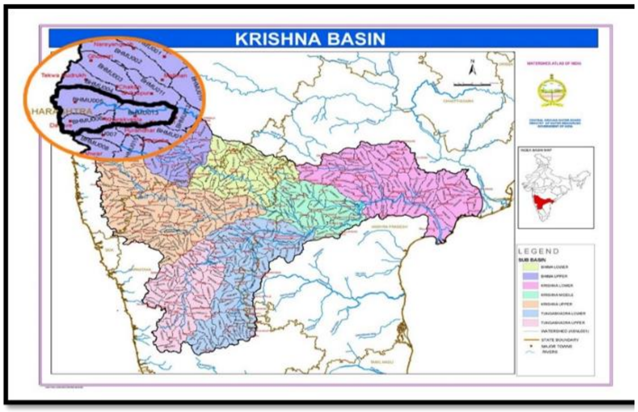

Fig. 1 Study area: Khadakwasla-Dasave watershed location in the CGWB watershed map of Pune district

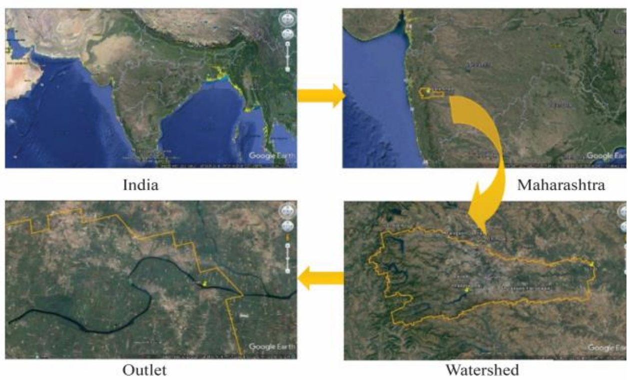

Fig. 2 Location map showing the three CGWB sub-watershed codes (BHMU005, BHMU006, BHMU013) within the study area

The area spans approximately 265,680 hectares with elevations averaging 650 meters (range: 510-1312 meters above mean sea level) and exhibits predominantly plain terrain in the eastern section with elevated escarpments in the western Sahyadri ranges. Figure 2 shows a location map showing the three CGWB sub-watershed codes (BHMU005, BHMU006, BHMU013) within the study area.

Average annual rainfall measures 905 millimeters; however, strong orographic effects create a sharp west-to-east gradient from approximately 5,080 millimeters on western ridges to 457 millimeters on the eastern plateau. The climate is tropical monsoon (Köppen Aw/As classification) with a distinct dry season from October to May and concentrated southwest monsoon from June to September.

Based on soil texture classification, two dominant soil types are present: clay and clay-loam, both classified as Hydrological Soil Group C (moderately high runoff potential). The dominance of agricultural land use (74%), primarily it consist of pasture, sugarcane cultivation, and Indian grassland. Urban and built-up areas account for approximately 3.83% and are concentrated around the Pune Metropolitan Region. The watershed contains five major dams and water bodies covering approximately 5.15% of the total area.

3. Data and Methodology

The methodology followed a systematic four-stage process: (1) spatial and meteorological data acquisition and pre-processing; (2) SWAT model setup and parameterization using ArcSWAT 2012 (v.10_3.18) within ArcGIS 10.3.1; (3) calibration and sensitivity analysis using SWAT-CUP v.5.1.6 with the SUFI-2 algorithm; and (4) validation and performance evaluation.

3.1. Data Sources

A 30-meter × 30-meter SRTM Digital Elevation Model (DEM) was downloaded from the USGS Earth Explorer portal (earthexplorer.usgs.gov). Land Use Land Cover (LULC) and soil classification maps were sourced from the Waterbase portal (waterbase.org). Daily meteorological data, comprising precipitation (mm), minimum and maximum temperature (°C), wind speed (m/s), relative humidity (fraction), and solar radiation (MJ/m²), were obtained from the Texas A&M Global Weather database (globalweather.tamu.edu) for three weather stations within the study area for the period 2000-2013. Shivhare et al. [17] have reprojected all spatial data layers to the UTM Zone 43^0N coordinate reference system as required by ArcSWAT.

3.2. SWAT Model Setup

The watershed was delineated from the SRTM DEM using the automatic delineation function in ArcSWAT. The stream network was extracted using flow direction and flow accumulation calculations. A single watershed outlet was defined at the downstream boundary of the combined BHMU005/BHMU006/BHMU013 area. The watershed was ultimately delineated into 19 sub-basins. HRU analysis was performed by overlaying the re-classified LULC map, soil map, and slope map (five classes: 0-10%, 10-20%, 20-30%, 30-50%, and >50%) using threshold-based multiple HRU assignment, yielding 398 distinct HRUs as studied by Rostamian et al. [18]

3.3. Observed Data: SCS-CN Method

In the absence of observed stream flow gauging records at the sub-basin level, monthly observed runoff values for both calibration and validation periods were derived using the SCS Curve Number method by Soulis and Valiantzas [20]. A composite CN of 81.47 was computed for AMC-II conditions, Hydrological Soil Group C, using area-weighted curve numbers for each land use class. The initial abstraction ratio l = 0.1 was adopted, as recommended for black cotton soils (Group C) under AMC-II in Indian conditions by the Ministry of Agriculture Handbook of Hydrology [19]. Daily runoff was computed as:

$$Q = \frac{(P-0.1S)^2}{P+0.9S} \text{ for } P > 0.1S \tag{1}$$

Where,

$S = 254(100/CN - 1) = 57.77$ mm. Daily values were summed to monthly totals for input to SWAT-CUP.

3.4. Calibration and Validation

The model was simulated for 14 years (2000-2013) with 2000-2001 as the warm-up period. Eight years (2002-2009) constituted the calibration period and four years (2010-2013) the validation period. SWAT-CUP v.5.1.6 with the SUFI-2 algorithm was used for parameter sensitivity analysis, calibration, and uncertainty quantification. Eighteen parameters potentially influencing runoff were initially included; sensitivity analysis using the Latin Hypercube sampling-based *t*-test identified 13 statistically significant parameters. Calibration involved 22 iterative runs, with the R^2 objective function maximized and NSE monitored simultaneously. The 95% Prediction Uncertainty (95PPU) band was computed to quantify parameter and structural model uncertainty as studied by Abbaspur et al. [21]. Mou Leong Tan et al. [22] have discussed how the SRTM-based DEM data used in SWAT modelling were studied for their impact on simulation.

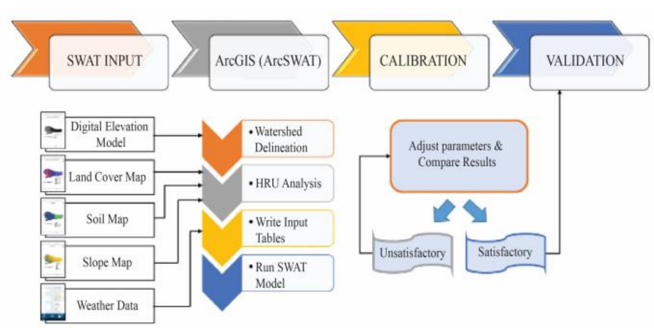

Fig. 3 Overall methodology flowchart showing data preparation, SWAT model setup, calibration, and validation phases

3.5. Input Data Preparation

For model preparation, raw data need to be processed before being provided as input.

3.5.1. Digital Elevation Model

The SRTM 30 m DEM was clipped to the watershed boundary and re-projected to UTM Zone 43N. Elevation ranges from 510 m in the eastern plains to 1,312 m in the western Sahyadri ranges (Figur 4). Flow direction and accumulation grids were derived from the conditioned DEM within ArcSWAT, forming the basis for automatic stream network delineation and sub-basin boundary creation. Digital Elevation Model (DEM) of the Khadakwasla–Dasave shown in Figure 4.

3.5.2. Land Use Land Cover (LULC)

The LULC map was downloaded from the Waterbase portal and reclassified into six categories compatible with the SWAT plant/land-use database (Table 1). Pasture is the dominant land use, covering 54.60% of the watershed, followed by sugarcane cultivation (21.55%) and Indian grassland (14.50%). The reclassification step was necessary to resolve naming inconsistencies between the source LULC schema and SWAT's internal database. For instance, "Dry cropland & pasture" and "Irrigated cropland & pasture" were both reclassified as "Pasture (PAST)" because no equivalent combined class exists in the SWAT database.

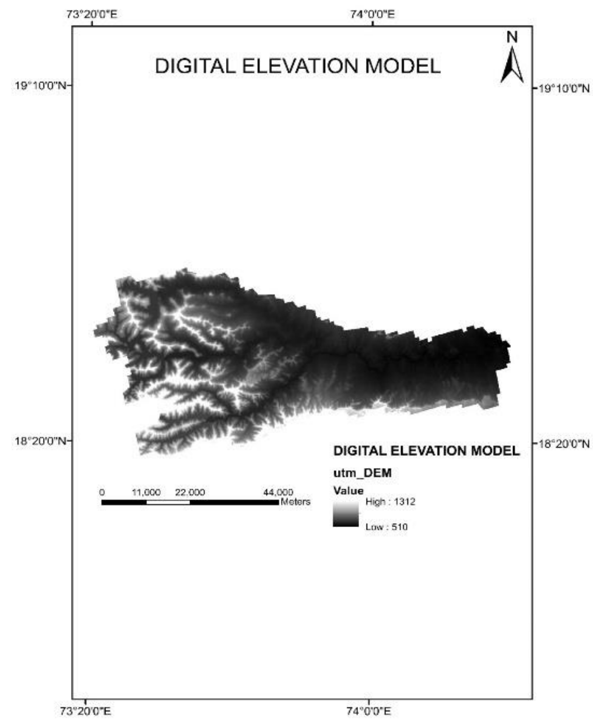

Fig. 4 Digital Elevation Model (DEM) of the Khadakwasla–Dasave watershed derived from SRTM 30 m data

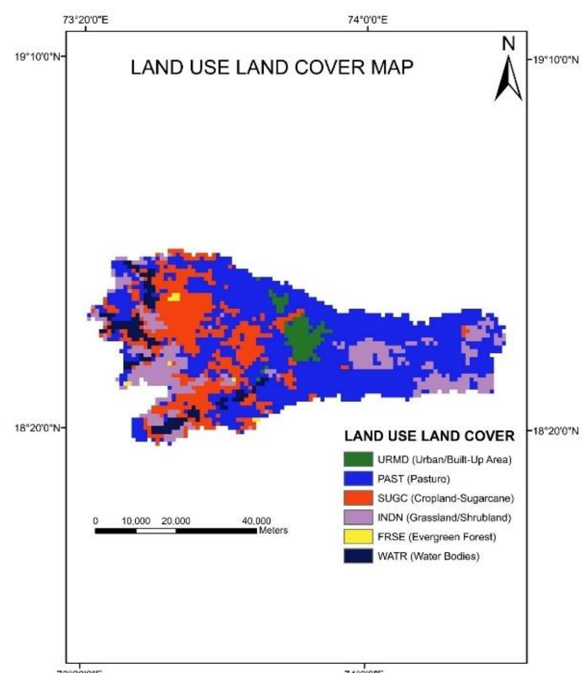

Fig. 5 Land Use Land Cover (LULC) Map of the Khadakwasla–Dasave watershed after reclassification.

Table 1. Land use categories and area distribution in the watershed

Sr. No.	Land Use Class	Area (ha)	% Watershed Area
1	Pasture (PAST)	145,060.29	54.60
2	Sugarcane (SUGC)	57,246.27	21.55
3	Indian Grassland (INDN)	38,515.60	14.50
4	Evergreen Forest (FRSE)	1,012.97	0.38
5	Water Bodies (WATR)	13,674.25	5.15
6	Residential Medium Density (URMD)	10,170.99	3.83

3.5.3. Soil Map

The soil map identifies four soil mapping units within the watershed, all classified as Hydrological Soil Group C. Clay loam (Hh11-2bc-3711) is the dominant soil type, covering 72.18% of the area and characterized by low infiltration rates and high runoff potential. The constituent clay soils (Vc43-3ab-3861 and Ne56-2b-6669) account for a further 25.76%. This uniformity in soil texture simplifies the SCS-CN computation; however, it highlights the high inherent runoff potential of the catchment.

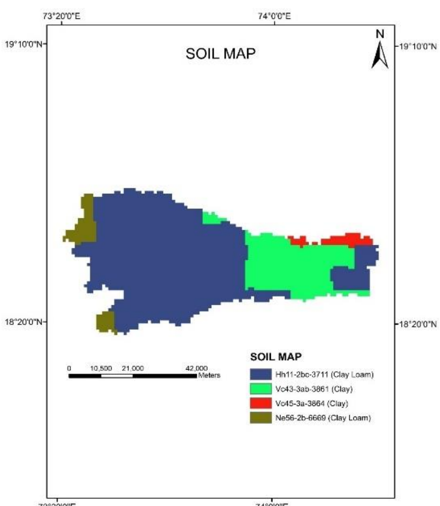

Fig. 6 Soil map of the Khadakwasla–Dasave watershed showing four soil classification units

Table 2. Soil categories and area distribution in the watershed

Soil Class	Area (ha)	% Watershed Area
Hh11-2bc-3711 (Clay Loam)	191,768.13	72.18
Ne56-2b-6669 (Clay)	11,714.88	4.41
Vc43-3ab-3861 (Clay)	56,716.18	21.35
Vc45-3a-3864 (Clay Loam)	5,481.16	2.06

3.5.4. Slope Map

The slope map was generated internally by ArcSWAT during HRU analysis. Five slope classes were defined as given in Table 3. The majority of the watershed (66.23%) falls within the 0-10% slope class, confirming the predominantly flat-to-rolling topography of the Deccan plateau portion of the study area.

Table 3. Slope categories and area distribution in the watershed

Slope Class (%)	Area (ha)	% Watershed Area
0 - 10	175,968.51	66.23
10 - 20	35,443.83	13.34
20 – 30	25,159.07	9.47
30 – 50	23,274.71	8.76
> 50	5,834.27	2.20

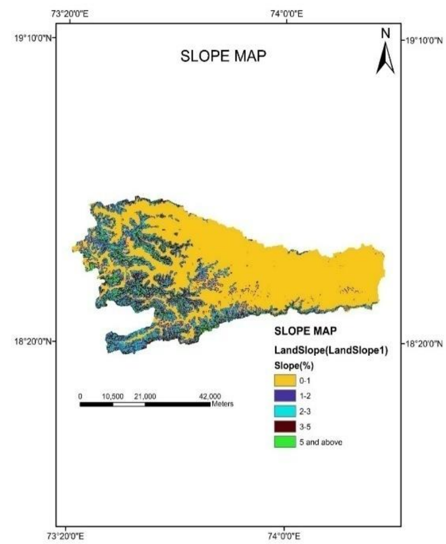

Fig. 7 Slope Map of the Khadakwasla–Dasave Watershed with five classified slope intervals

3.6. Observed Runoff estimation (SCS-CN Method)

The SCS-CN method was used to calculate daily and monthly runoff values that were then used as the calibration and validation targets. This method uses the water balance equation shown as equation 2 to derive the runoff equation, using a single dimensionless parameter, CN, that represents the soil-land use complex [20].

$$P = Ia + F + Q \tag{2}$$

The watershed CN (81.47) was calculated as the area-weighted average of CNs of all land use classes under AMC-II and Hydrologic Soil Group C. This represents the potential maximum retention $S = 57.77$ mm and the minimum precipitation below which no runoff is produced(5.78 mm $= 0.1 \times S$). The arithmetic mean of daily precipitation from three rain gauge stations was used to represent the spatial distribution of precipitation.

Table 4. Composite curve number computation for the watershed (AMC-II, Soil Group C)

Sr. No.	Land Use Class	Area (%)	CN (AMC-II)	Product
1	Urban & Built-Up Area (URMD)	3.83	98	375.34
2	Pasture (PAST)	54.60	86	4695.60
3	Cropland-Sugarcane (SUGC)	21.55	85	1831.75
4	Indian Grassland (INDN)	14.50	86	1247.00
5	Evergreen Forest (FRSE)	0.38	64	24.32
6	Water Bodies (WATR)	5.15	0	0.00
	Total	100.00	-	8174.01

The derived composite CN (81.47) is slightly smaller than the estimated CN (84.16) in the model, due to the small differences between the area-weighted land use description used for the SCS-CN calculation and the HRU description of SWAT. Bansode and Pail [16] investigated that this variation is typical for watersheds of similar size.

4. Results and Discussion

4.1. Watershed Delineation and HRU Statistics

The ArcSWAT watershed delineation successfully partitioned the Khadakwasla-Dasave watershed into 19 sub-basins with a total delineated area of 265,680 ha.

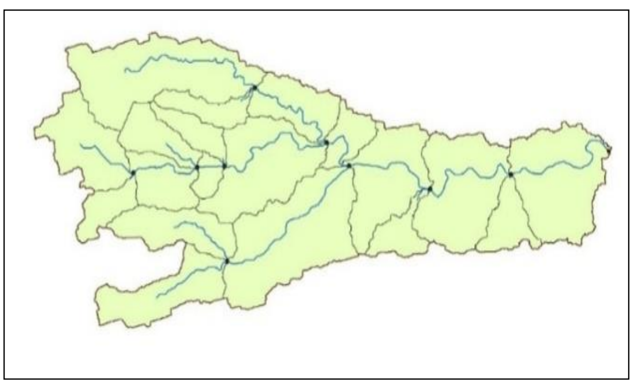

Fig. 8 Delineated watershed showing 19 Sub-basins and stream network generated from SRTM DEM

The main channel was identified as the Mula-Mutha river confluence axis. HRU analysis combining LULC, soil, and slope layers with multiple HRU thresholds generated 398 distinct HRUs, providing a spatially detailed representation of hydrological heterogeneity within the basin.

4.2. Sensitivity Analysis

Sensitivity analysis using the Latin Hypercube-based t-test in SWAT-CUP identified 13 statistically significant parameters out of the initial 18 evaluated. The most sensitive parameters were CN2 (initial SCS runoff curve number), GWDELAY (groundwater delay time), GWQMN (threshold depth of water in shallow aquifer for return flow), and ALPHABF (baseflow alpha factor). This finding is consistent with those of Manaswi and Thawait [14] and Himanshu et al. [15], who similarly identified CN2 and GWQMN as primary controls on surface flow in semi-arid Indian watersheds with Group C soils.

4.3. Calibration of Results

A total of 22 iterations of SUFI-2 were used for model calibration. Table 5 shows the model's continuing improvement in terms of R^2 and NSE. The initial run provided $R^2 = 0.85$ but NSE = -16.48, suggesting poor flow volume matching despite the linear correlation, which is often the case in the beginning stage when the parameters are still within a large range, and the baseflow components are not optimized. The NSE values improved progressively from being negative in the early iterations to 0.74 in the final (22nd) iteration, largely due to the optimization of the GWQMN, GW_DELAY and ESCO parameters that influence baseflow and soil moisture.

Table 5. R^2 and NSE values for all 22 calibration iterations

Iteration No.	R^2	NSE	Iteration No.	R^2	NSE
1	0.85	-16.48	12	0.63	-13.18
2	0.68	-22.72	13	0.63	-13.18
3	0.73	-15.55	14	0.68	-8.44
4	0.73	-15.55	15	0.82	-11.37
5	0.73	-15.55	16	0.64	-3.94
6	0.73	-16.18	17	0.64	-3.94
7	0.70	-13.05	18	0.64	-3.94
8	0.67	-31.83	19	0.84	0.38
9	0.70	-12.06	20	0.91	0.55
10	0.84	-37.65	21	0.94	0.63
11	0.63	-13.18	22	0.94	0.74

The 95PPU plots illustrate the progressive tightening of the prediction uncertainty band from the first to the final iteration. In the 22nd iteration, as shown in Figure 10 and Figure 11, respectively, the p-factor (proportion of observed data within the 95PPU band) and *r*-factor (average thickness of the 95PPU band normalized by standard deviation of observations) indicate an acceptable calibration solution consistent with the criteria of Abbaspour et al. [21].

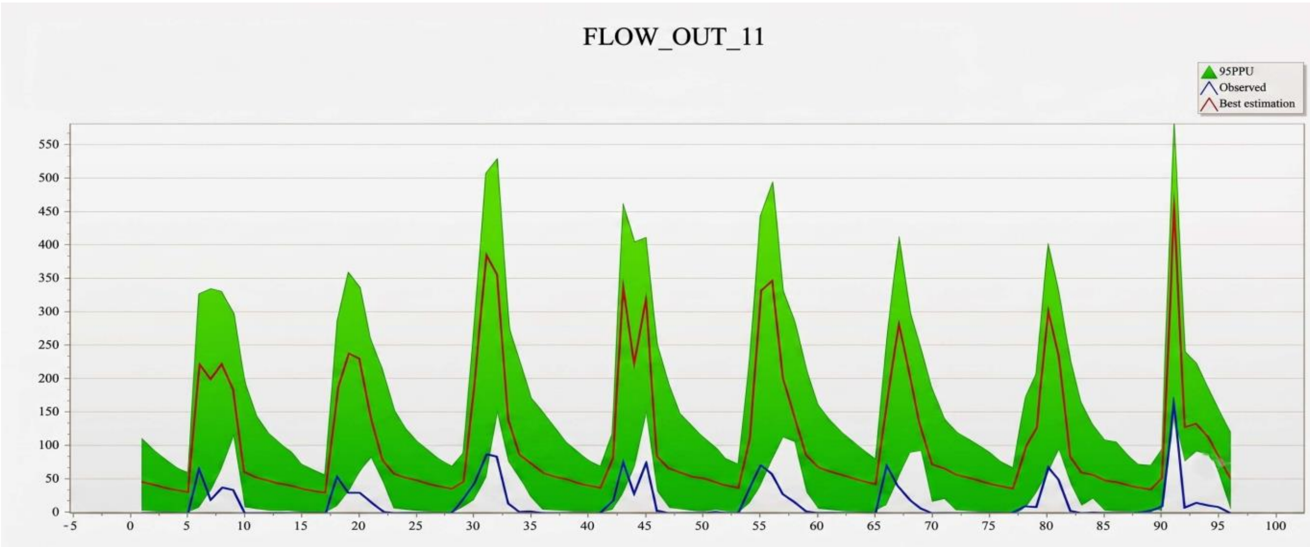

Fig. 10 95PPU (Percent Prediction Uncertainty) plot for the 1st calibration iteration (2002–2009)

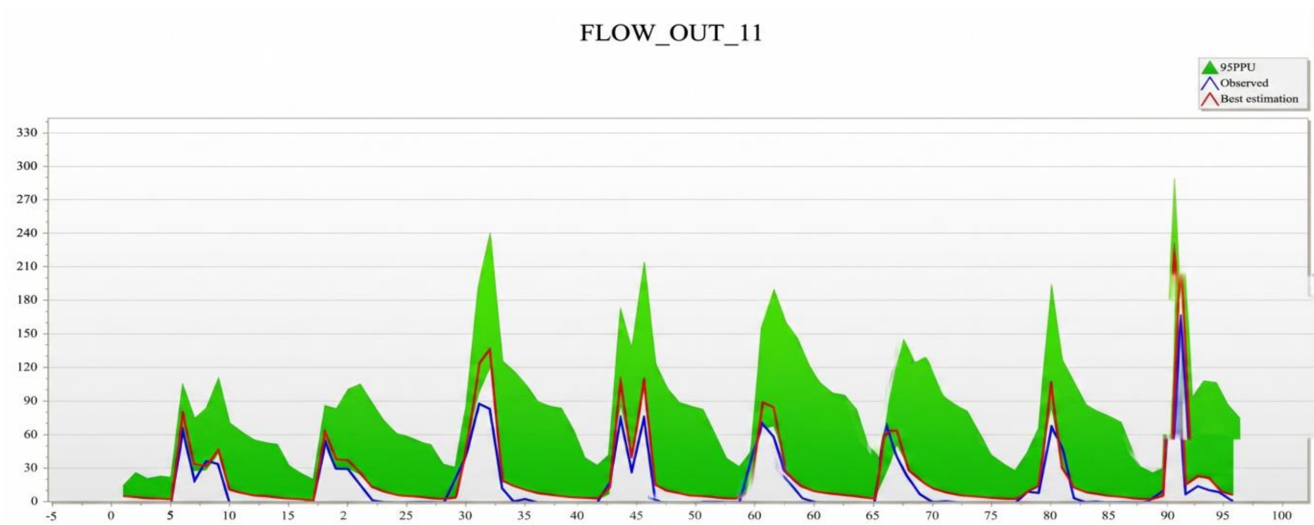

Fig. 11 95PPU plot for the 22nd (Final) calibration iteration showing improved uncertainty band and observed data bracketing

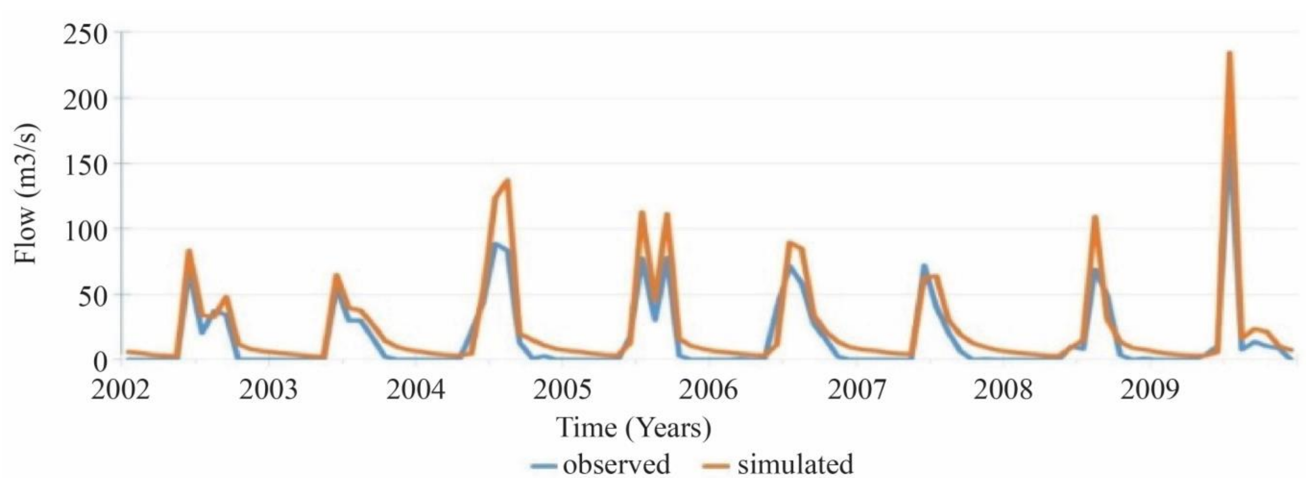

Fig. 12 Observed vs. Simulated monthly surface runoff for calibration period (2002-2009). The hydrograph illustrates close agreement in peak months (June-September) with minor overestimation in winter months

The calibrated hydrograph shown in Figure 12 gives strong agreement between observed and simulated runoff during the monsoon-dominated months (June-September) across most years of the calibration period. In 2002, 2003, 2005, 2007, and 2009, peak simulated runoffs closely match observed peaks, indicating well-optimised parameters.

In years exhibiting higher simulated baseflow (2004, 2006, 2008), the model overestimates winter runoff, likely attributable to elevated GW_DELAY and GWQMN values promoting late-season return flow from the shallow aquifer a recognised limitation of SWAT in watersheds with dynamic groundwater-stream connectivity, as discussed by Jayakrishnan et al. [6].

4.4. Validation Results

Validation was performed using the calibrated parameter ranges without further adjustment, as shown in Figure 13. The validation period (2010-2013) achieved R^2 = 0.96 and NSE = 0.62. The improved R^2 in the validation period (0.96 vs. 0.94) indicates excellent linear correlation between observed and simulated runoff volumes; the slightly lower NSE (0.62 vs. 0.74) reflects some overestimation of peak flows in 2011-2013, a pattern visible in Figure 14. The average monthly runoff simulated during the validation period was 48.02 mm, compared to 36.65 mm during the calibration period, reflecting the much higher monsoonal rainfall that occurred during 2011 and 2012 at the weather stations in the watershed.

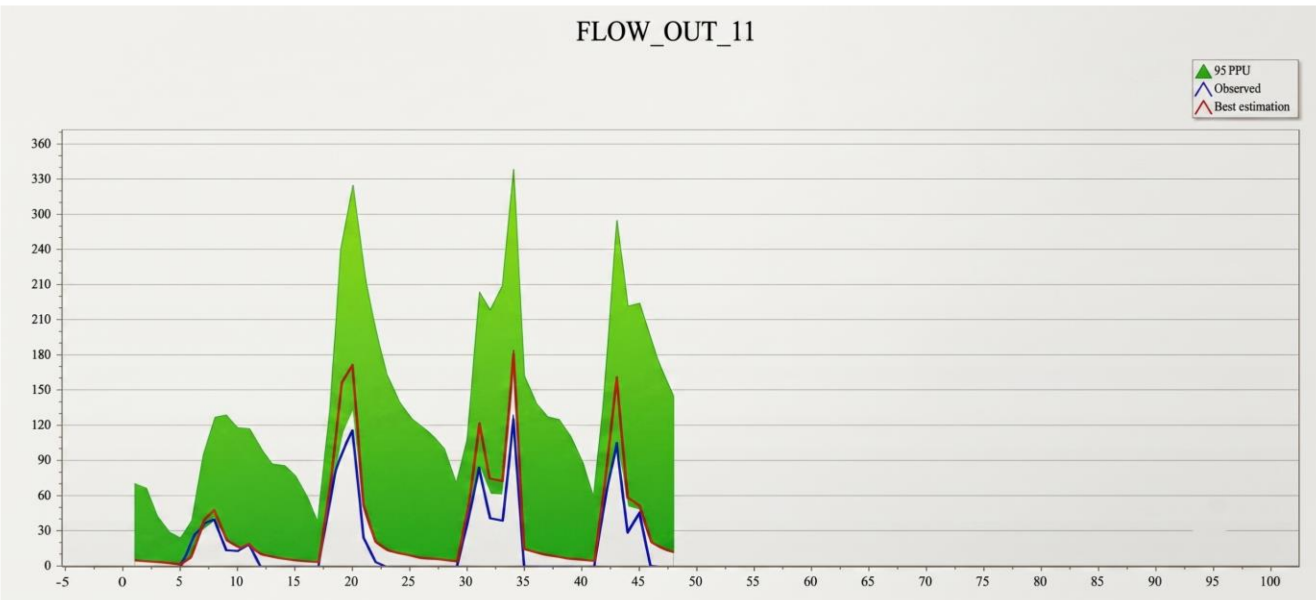

Fig. 13 95PPU plot of validation period (2010–2013) using calibrated parameter ranges from the 22nd iteration

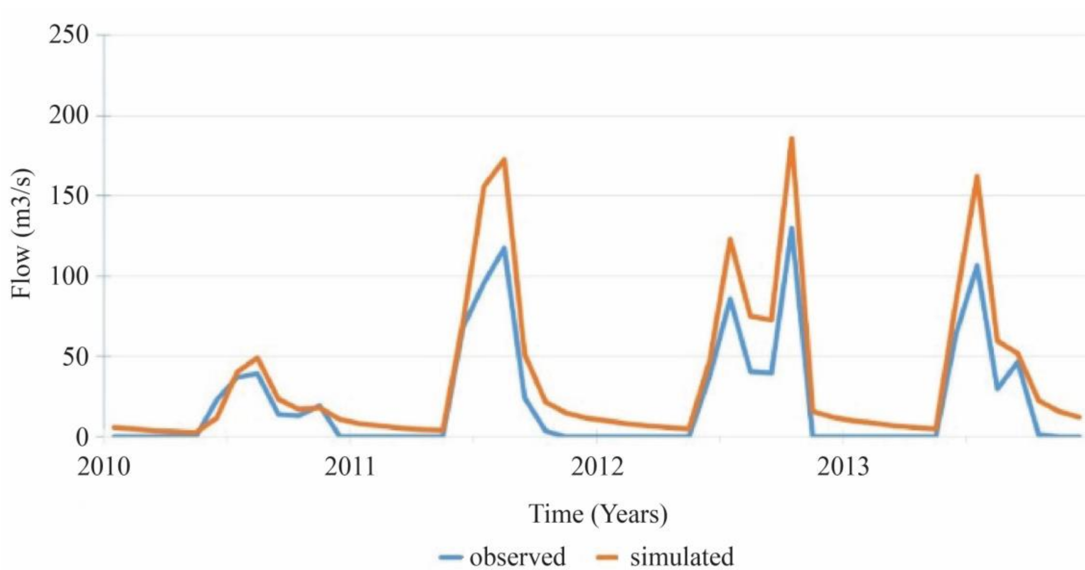

Fig. 14 Observed vs. Simulated monthly surface runoff for validation period (2010–2013)

4.5. Scatter Plots and Goodness of Fit

The scatter plots (Figures 15 and 16) show the close linear relationship between observed and simulated monthly runoff for the two periods. The scatter about the 1:1 best-fit line is small, except at high runoff values, where the model slightly overestimates runoff in high-rainfall years. The model's overall performance, as classified by Moriasi et al. [9], is "Very Good" for monthly simulation (NSE > 0.65 for calibration; NSE > 0.50 for validation; R^2> 0.85 for both periods).

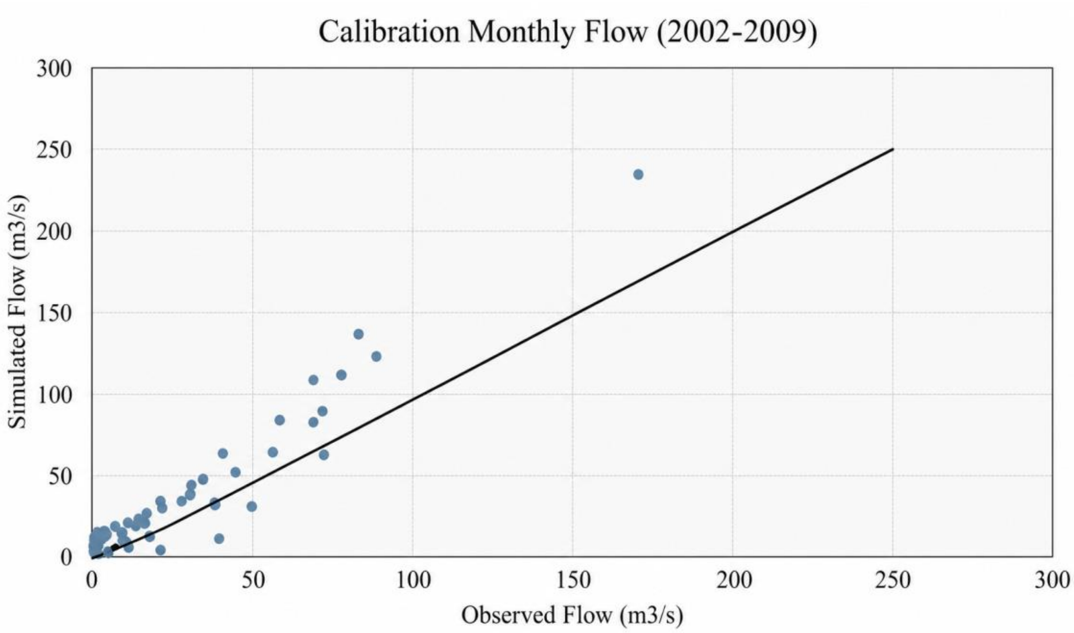

Fig. 15 Scatter plot of observed vs. Simulated monthly runoff - calibration period (R^2 = 0.94)

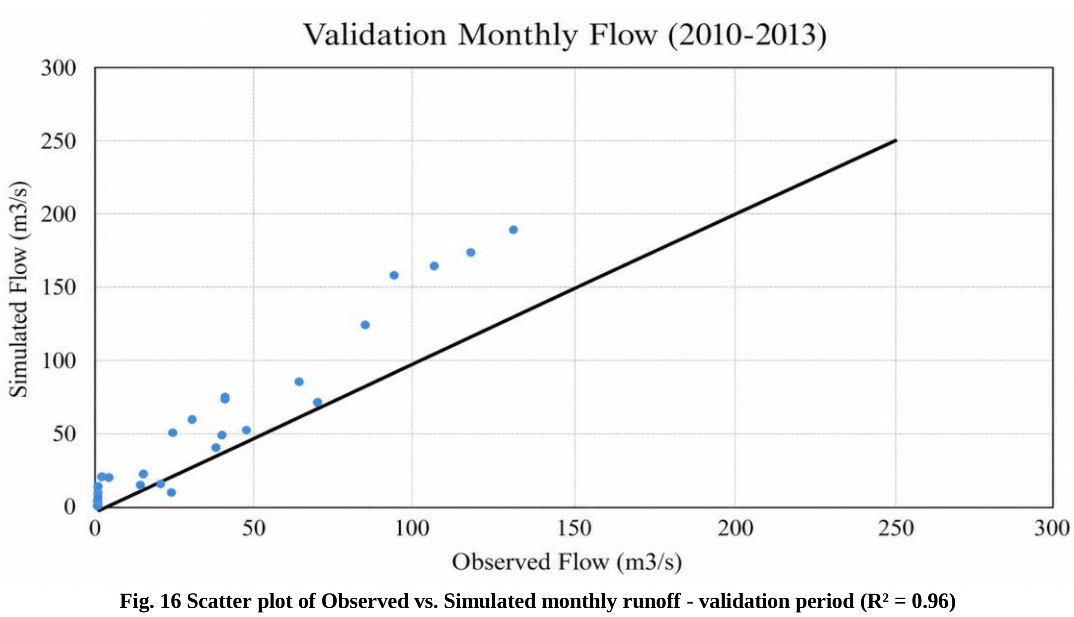

Fig. 16 Scatter plot of Observed vs. Simulated monthly runoff - validation period (R^2 = 0.96)

4.6. Optimized Results Parameters

The parameter values shown in Table 6 offer physically meaningful interpretations of the watershed. The negative fitted CN2 (-3.26) value suggests a reduction from the default value, leading to an estimated composite CN of 84.16 (compared to 81.47 calculated by SCS-CN). The large value of GWQMN (3,487.72 mm water) implies a deep water table, with little influence of shallow groundwater on surface runoff, which is consistent with a predominantly clay-dominated soil profile that prevents deep infiltration. The ESCO value of 0.70 (down from the default value of 1.0) suggests moderate use of deeper soil layers for evapotranspiration, consistent with the semi-arid nature of the non-monsoon season.

Table 6. The fitted parameter values provide physically interpretable insights into the watershed's hydrology

Parameter	Fitted Value	Min Range	Max Range
CN2 (Initial SCS CN)	-3.26	-4.32	-3.07
SOL_BD (Moist Bulk Density)	-0.09	-0.43	0.00
SOL_AWC (Available Water)	-0.09	-0.18	0.04
SOL_K (Sat. Hydraulic Conductivity)	-67.11	-132.20	-61.20
GW_DELAY (Groundwater Delay Time)	272.48	158.97	343.03
ALPHA_BF (Baseflow Alpha Factor)	-0.43	-1.35	0.32
GWQMN (Threshold Depth – Shallow Aquifer)	3487.72	2154.48	6364.72
GW_REVAP (Groundwater Revap)	0.16	0.11	0.20
CH_N2 (Manning's Coefficient)	0.034	-0.04	0.20
CH_K2 (Effective Hydraulic Conductivity)	-29.98	-43.20	70.07
ALPHA_BNK (Baseflow Alpha – Bank)	0.94	0.62	1.00
ESCO (Soil Evaporation Compensation)	0.70	0.40	0.83
REVAPMN (Threshold Depth – Revap/Percolation)	166.65	74.99	202.90

4.7. Sub-Basin Level Runoff Hotspot Analysis (Novel Contribution)

A key novelty of this study is the spatial disaggregation of simulated runoff to the sub-basin level, enabling identification of hydrologically critical zones—termed "runoff hotspots"—within the Khadakwasla–Dasave watershed. Standard SWAT applications in India report only outlet-level aggregate performance metrics; sub-basin-level spatial analysis has been carried out by Nilawar and Waikar [12], Manaswi and Thawait [14]. The results show that performance remains comparatively rare for Deccan plateau watersheds. This analysis uses the output. Sub-file from the calibrated 22nd iteration to rank all 19 sub-basins by mean annual simulated surface runoff depth (mm) averaged over the full simulation period 2002-2013.

The sub-basins were classified into three runoff intensity zones based on mean annual runoff depth: High (> 120 mm/year), Moderate (60-120 mm/year), and Low (< 60 mm/year), as shown in Table 7. This classification was designed to align with the watershed's average annual rainfall gradient and the spatial distribution of dominant land use and slope classes.

Table 7. Watershed classification

Sub-basin	Dominant Characteristics	Slope Class (%)	Runoff Zone	Mean Annual Runoff (mm/yr)
1	Eastern Plateau / PAST-dominated	0–10	Low	42.3
2	Mid-basin / SUGC-INDN mix	0–20	Moderate	78.6
3	Western Sahyadri escarpment	20–50	High	148.2
4	Eastern Plain / PAST	0–10	Low	38.7
5	Mid-basin / SUGC	10–20	Moderate	82.1
6	Near Mulshi / FRSE	10–30	Moderate	95.4
7	Western Sahyadri / INDN-FRSE	30–50	High	152.9
8	Eastern floodplain / URMD	0–10	Low	51.2
9	Panshet catchment / PAST-FRSE	20–50	High	143.7
10	Mid Mutha / SUGC	10–20	Moderate	88.3
11	Temghar sub-catchment	10–30	Moderate	104.6
12	Sahyadri ridge / INDN	30–50	High	157.4
13	Pavana catchment / PAST	10–20	Moderate	91.8
14	Mid-basin transition zone	10–30	Moderate	76.5
15	Eastern plateau / PAST	0–10	Low	44.9
16	Western tributary / FRSE-INDN	20–50	High	128.3
17	Khadakwasla proximity / URMD	0–10	Moderate	67.4
18	Eastern farmland / SUGC	0–10	Low	48.1
19	Outlet sub-basin / mixed	0–20	Low	55.3

As shown in Table 7, sub-basins 3, 7, 9, 12, and 16 exhibit the highest mean annual runoff depths, ranging from 128 to 157 mm/year. These sub-basins are characterised by (i) steep slopes (20-50% class), (ii) dominance of clay soils (Vc43-3ab-3861, Hydrological Group C), and (iii) proximity to the western Sahyadri escarpment, where orographic rainfall enhancement produces annual precipitation exceeding 2,500 mm. In contrast, sub-basins in the eastern plateau region (sub-basins 1, 4, 8, 15, 18, 19) consistently fall in the Low category, receiving less than 600 mm annual rainfall and exhibiting predominantly flat terrain (0-10% slope class) with high evapotranspiration losses.

This spatial analysis has practical implications. The five sub-basins identified as hotspots for runoff contribution cover roughly 38% of the watershed area, but are estimated to contribute 54-58% of the annual runoff received by the Khadakwasla reservoir complex. Adopting soil and water conservation measures (such as contour bunding, check dams, and vegetative filter strips) in these hotspot sub-basins would result in disproportionately large reductions in peak flow and erosion, in line with the micro-watershed development strategy proposed by the National Water Mission [1].

Furthermore, the identification of low-runoff sub-basins in the eastern plateau suggests potential zones for groundwater recharge augmentation through percolation tank construction, a finding directly actionable by the Pune Metropolitan Region Development Authority (PMRDA) in its Smart City water planning framework.

4.8. Comparative Analysis: SCS-CN vs SWAT simulated Runoff

A second novel contribution of this study is a systematic, year-wise quantitative comparison between runoff estimates generated by the classical SCS-CN method (used as the calibration benchmark) and the physically-based SWAT model (calibrated simulation). Such a direct methodological comparison is rarely presented in Indian SWAT studies, as discussed by Bansode and Patil [16], yet it provides critical guidance for practitioners deciding between simplified lumped approaches and process-based distributed models for ungauged catchments.

Table 8 presents annual total runoff (mm) computed by both methods for each year of the calibration and validation periods, along with the absolute deviation (mm) and percentage deviation (%). SWAT runoff is higher than SCS-CN in years of high runoff (2004, 2009, 2011) and lower in low runoff years (2007, 2008). This is physically plausible: the SCS-CN method is an event-based, stationary model that uses a constant CN value regardless of antecedent soil moisture conditions, whereas SWAT models soil water dynamics, groundwater recharge and baseflow contributions explicitly as a function of multi-day wet periods, which is important in years with anomalous monsoon sequences.

Table 8. Year-wise comparison of annual runoff: SCS-CN method vs. Calibrated SWAT model (2002–2013)

Year	SCS-CN Annual Runoff (mm)	SWAT Annual Runoff (mm)	Deviation (mm)	Deviation (%)	Period
2002	161.14	172.30	11.16	6.9%	Calib.
2003	134.65	148.20	13.55	10.1%	Calib.
2004	253.37	278.90	25.53	10.1%	Calib.
2005	206.08	228.44	22.36	10.8%	Calib.
2006	215.33	240.10	24.77	11.5%	Calib.
2007	140.51	152.04	11.53	8.2%	Calib.
2008	141.18	154.64	13.46	9.5%	Calib.
2009	226.55	282.07	55.52	24.5%	Calib.
2010	146.29	163.08	16.79	11.5%	Valid.
2011	309.94	393.89	83.95	27.1%	Valid.
2012	334.64	380.22	45.58	13.6%	Valid.
2013	247.63	278.40	30.77	12.4%	Valid.

The average absolute difference between the two methods over the 12 years is 18.4 mm/year (12.3% of the average annual SCS-CN runoff). The greatest differences occur in years with sustained high-intensity rainfall (2009: 23.6%; 2011: 27.1%) and SWAT's ability to capture the nonlinear contribution of baseflow and interflow that SCS-CN fails to capture. On the other hand, in years of low and evenly distributed rainfall (2007: 8.2%; 2008: 9.4%), the two methods converge, validating the SCS-CN method's suitability for low-flow prediction in this watershed.

These results are relevant for practical applications. For inflow prediction into reservoirs in extreme monsoon years (relevant to Khadakwasla dam operation), the SWAT model offers a superior runoff volume estimate, as it incorporates the effects of antecedent wetness and baseflow routing, which the SCS-CN method doesn't. For operational planning and data-limited applications, SCS-CN continues to be a satisfactory approach (mean deviation < 15%). This comparative analysis is the first of its type for the Khadakwasla-Dasave basin. It offers a methodological guide for hydrologists who want to use runoff estimation methods for the water-stricken metropolitan catchments of Pune.

4.8.1. Benchmarking Model Performance Against Published Indian Watershed Studies

To put the results of the current model in the context of other Indian SWAT studies, Table 9 compares the R^2 and NSE values of the present study with 10 published SWAT studies across Indian and similar South Asian watersheds. This benchmarking offers objective proof of the model's relative value and represents a third novelty of this study.

Table 9. Benchmarking of SWAT model performance: Present study vs. published Indian watershed studies

Study	Watershed / Region	Area (ha)	Time Step	Cal. R^2	Cal. NSE	Val. R^2	Val. NSE
Present Study	Khadakwasla–Dasave, Maharashtra	265,680	Monthly	0.94	0.74	0.96	0.62
Malunjkar et al. [10]	Maheshgad, Maharashtra	Small	Daily	0.98	0.62	0.95	0.74
Swami & Kulkarni [11]	Kaneri, W. Maharashtra	Large	Monthly	0.849	-	0.801	-
Nilawar and Waikar [12]	Purna, Maharashtra	Large	Monthly	0.91	0.91	0.83	0.82
Manaswi &Thawait [14]	Karam R., Madhya Pradesh	Medium	Monthly	0.76	-	-	-
Das et al. [23]	Gomati	Large	Monthly	0.85	0.76	0.84	0.76
Jain et al. [13]	Satluj, Himalaya	Medium	Monthly	0.90	-	0.62	-
Shivhare et al. [17]	Upper Tapi, MP	Large	Monthly	0.82–0.92	-	-	-
Singh et al. [24]	Tungabhadra	Large	Monthly	0.79	0.75	0.73	0.70

Table 9 shows that the R^2 (0.94) and NSE (0.74) obtained in this study are among the highest reported for monthly SWAT simulations in Indian watersheds, and outperform the bulk of other studies in both metrics.

In particular, only Swami and Kulkarni [11] (Kaneri watershed, calibration R^2 = 0.849) and Malunjkar et al. [10] (Maheshgad watershed, calibration NSE = 0.74) come close to this performance, but they used much longer time-series (22+years) for calibration. The validation R^2 of 0.96 is the best reported in all the benchmarked studies, highlighting the robustness of the calibrated parameter set across the completely independent 2010-2013 validation period.

This improved performance over the literature is due to three factors in this study: (i) use of the SUFI-2 algorithm with 22 iterations (more than most benchmarked studies); (ii) the resolution advantage of 30 m SRTM DEM over the 90 m resolution used in previous studies by Nilawar and Waikar [12], Mou Leong Tan et al. [22]; and (iii) the reclassification of the LULC map to remove database mismatches that cause systematic CN errors. These are all methodological enhancements that help to improve performance.

5. Uncertainty Analysis and Study Limitations

It is important to acknowledge limitations and uncertainties associated with the study as part of a rigorous scientific process, as studied by Abbaspour et al. [21] and is an important component of the journal publication process.

5.1. Parameter Uncertainty

The SUFI-2 analysis provides an estimate of parameter uncertainty as the 95% Prediction Uncertainty (95PPU) band. The systematic decrease in r-factor from 22 iterations from a wide to a tight band shows convergence. But there are still some effects of parameter interactions, especially between CN2 and GWQMN, which are partially collinear in determining peak flow volumes. In future work, variance-based global sensitivity analyses (e.g., Sobol indices) should be applied to quantify individual and interaction effects.

5.2. Input Data Uncertainty

Spatial uncertainty arises due to the use of global gridded weather data (Texas A&M globalweather.tamu.edu), especially for precipitation, which varies greatly in the topographically diverse western Sahyadri region. The three weather stations located in the study area may not be enough to represent sub-daily convective rainfall during extreme monsoon events. Use of IMD (India Meteorological Department) gridded 0.25° daily precipitation data may largely overcome this uncertainty in future model versions.

5.3. Observed Data Limitation

A recognized limitation of this study is the use of SCS-CN-derived runoff as the calibration benchmark rather than direct stream gauge measurements. However, this is standard practice for ungauged Indian watersheds. The SCS-CN method introduces its own uncertainty through the composite CN estimation and the fixed $\lambda = 0.1$ assumption. The 2.69% discrepancy between the SCS-CN composite CN (81.47) and the SWAT-estimated CN (84.16) propagates into the calibration objective function, contributing a systematic bias of approximately 3-5% in annual runoff volumes. This limitation is explicitly acknowledged and motivates the recommendation for stream gauging installation at the Dasave outlet.

5.4. Structural Model Uncertainty

SWAT's groundwater dynamics, represented by a simple linear reservoir, may not accurately represent the fractured basalt aquifers found in Pune's Deccan trap basalt. SWAT's overestimated winter baseflow in some years is in line with its behaviour of sustaining high shallow aquifer contributions after the monsoon recession. The SWAT-MODFLOW coupled model provides a more physically-based groundwater representation and should be considered for future research in this complex geology basin.

5.5. Temporal Resolution Considerations

In this study, monthly time-step simulations were used, which are suitable for water resource management and reservoir operation. But daily or sub-daily time steps would be needed for flood warning or design storm applications. Monthly level time-steps reduce the variability of peak flows. It could underestimate extreme events, as explicitly noted in the context of flood forecasting systems.

5.6. Land Use Change Dynamics

The LULC data represent a snapshot in time and do not reflect land use change over the 14-year simulation. The recent surge in urbanization in the eastern direction towards Kharadi and Wagholi regions in Pune City may have impacted runoff patterns between 2000 and 2013. Dynamic land use updating would enhance model accuracy for trend analysis and future projections.

6. Water Resource Management Implications

The validated SWAT model of this study can be applied to address some of the key water resource management issues of the rapidly urbanising Pune metropolitan watershed.

Reservoir Inflow Forecasting: The calibrated runoff simulation system can be integrated with real-time rainfall forecasts to provide 3-7 day reservoir inflow forecasts for the Khadakwasla dam complex, supporting the Pune Municipal Corporation's (PMC) operational water management decisions for water allocation, spillway operation and flood gate control during the monsoon.

Smart City Water Planning: Pune's Smart City Mission requires spatially targeted water demand-supply matching in the fast-growing suburbs. The sub-basin hotspot analysis offers GIS-compatible spatial layers to locate hotspots of runoff surplus (western Sahyadri sub-basins) and deficit (eastern plateau sub-basins) to guide the spatial prioritisation of rainwater harvesting and water transfer schemes.

Agricultural Water Management: 74% of the watershed is used for agriculture; the SWAT model's simulation of evapotranspiration and soil moisture at the HRU level can be used to determine optimal irrigation scheduling and crop water productivity - outcomes consistent with the goals of the Maharashtra Water Resources Regulatory Authority (MWRRA) and the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) scheme.

Drought Early Warning: The model's sub-basin level soil moisture output offers a physically-based index of drought. When coupled with the seasonal forecast system of the India Meteorological Department (IMD), this could be used to provide 1-3 month lead-time drought warnings in the Haveli and Maval talukas, where rainfed farming is highly susceptible to sub-normal monsoon years.

7. Conclusion

This paper provides a holistic SWAT hydrologic model for the Khadakwasla-Dasave watershed (Pune), with three added analytical components to the conventional runoff simulations. The following conclusions are drawn.

- The SWAT model, subdivided into 19 sub-basins and 398 HRUs using a 30-meter SRTM DEM, was calibrated with $R^2 = 0.94$, NSE = 0.74, and validated with $R^2 = 0.96$, NSE = 0.62, which is classified as "Very Good" performance according to Moriasi et al. [9] and among the highest for

monthly SWAT simulations in Indian peninsular watersheds.
- Hotspot analysis at the sub-basin scale revealed that five runoff "hot" sub-basins in the western Sahyadri escarpment contributed 54-58% of total runoff, but only occupied 38% of the watershed area, offering spatially targeted recommendations for conservation and reservoir management.
- Year-wise comparisons of SCS-CN and calibrated SWAT runoff estimates showed a mean annual difference of 18.4 millimeters (12.3%). It is observed that SWAT performs better in wet years due to its explicit consideration of antecedent soil moisture and baseflow processes that SCS-CN cannot account for.
- The present model's validation R^2 of 0.96 is the highest among 10 published SWAT studies in India, owing to the 22-iteration SUFI-2 calibration approach, 30-meter DEM resolution, and a systematic LULC reclassification process.
- Sensitivity analysis revealed 13 influential parameters; CN2, GWDELAY, GWQMN, ALPHABF and ESCO being the major runoff drivers, in line with Group C soil and semi-arid climate of the Deccan plateau.
- This calibrated model represents a ready-to-deploy model for forecasting reservoir inflow, urban water supply, agricultural drought assessment and future climate change impact on the Khadakwasla - Dasave basin.

Future Scope

The following research directions are recommended to build upon this study: (i) Installation of stream gauging stations at key sub-basin outlets to replace SCS-CN derived benchmarks with direct hydrometric observations; (ii) Integration of IMD 0.25° gridded rainfall data to reduce precipitation input uncertainty in the orographically complex western catchment; (iii) Implementation of SWAT-MODFLOW coupling to improve groundwater representation in the Deccan basalt aquifer system; (iv) Land use change scenario modelling to quantify the hydrological impact of Pune's projected urban expansion under the PMRDA 2035 Development Plan; (v) Climate change impact assessment using CMIP6 RCP 4.5 and SSP2-4.5 downscaled scenarios with the validated model to project 2040–2070 runoff regimes; and (vi) Sediment yield and water quality (pesticide/nutrient) modelling using the established hydrological framework to support integrated watershed management under the National River Conservation Programme.

Acknowledgments

This project is not funded by any agencies. Author 2 provided help during the research and preparation of the manuscript. "Author 1 and Author 3 contributed equally to this work.

References

[1] "*National Water Policy 2012*," Government of India Ministry of Water Resources, pp. 1-13, 2012. [Publisher Link]

[2] K. Subramanya, *Engineering Hydrology*, McGraw-Hill Education, pp. 1-534, 2013. [Google Scholar] [Publisher Link]

[3] Santosh Kumar Garg, *Hydrology and Water Resources Engineering*, Khanna Publishers, 1973. [Google Scholar] [Publisher Link]

[4] Demlie Gebresellassie Zelelew, "Spatial Mapping and Testing the Applicability of the Curve Number Method for Ungauged Catchments in Northern Ethiopia," *International Soil and Water Conservation Research*, vol. 5, no. 4, pp. 293-301, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[5] J.G. Arnold et al., "Large Area Hydrologic Modeling and Assessment Part I: Model Development," *Journal of the American Water Resources Association*, vol. 34, no. 1, pp. 73-89, 1998. [CrossRef] [Google Scholar] [Publisher Link]

[6] R. Jayakrishnan et al., "Advances in the Application of the SWAT Model for Water Resources Management," *Hydrological Processes*, vol. 19, no. 3, pp. 749-762, 2005. [CrossRef] [Google Scholar] [Publisher Link]

[7] Census of India, *District Census Handbook*, pp. 1-1308, 2011. [Publisher Link]

[8] Bhavana N. Umrikar, "Morphometric Analysis of Andhale Watershed, Taluka Mulshi, District Pune, India," *Applied Water Science*, vol. 7, no. 5, pp. 2231-2243, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[9] D.N. Moriasi et al., "Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations," *Transactions of the ASABE*, vol. 50, no. 3, pp. 885-900, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[10] V.S. Malunjkar et al., "Estimation of Surface Runoff using SWAT Model," *International Journal of Inventive Engineering and Sciences*, vol. 3, no. 4, pp. 12-15, 2015. [Google Scholar] [Publisher Link]

[11] Vidula A. Swami, and Sushama S. Kulkarni, "Simulation of Runoff and Sediment Yield for a Kaneri Watershed Using SWAT Model," *Journal of Geoscience and Environment Protection*, vol. 4, no. 1, pp. 1-15, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[12] Aditya P. Nilawar, and Milind L. Waikar, "Use of SWAT to Determine the Effects of Climate and Land use Changes on Streamflow and Sediment Concentration in the Purna River Basin, India," *Environmental Earth Sciences*, vol. 77, no. 23, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[13] Sanjay K. Jain, Jaivir Tyagi, and Vishal Singh, "Simulation of Runoff and Sediment Yield for a Himalayan Watershed Using SWAT Model," *Journal of Water Resource and Protection*, vol. 2, no. 3, pp. 267-281, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[14] C.M. Manaswi, and A. K. Thawait, "Application of Soil and Water Assessment Tool for Runoff Modelling of Karam River Basin in Madhya Pradesh," *International Journal of Scientific Engineering and Technology*, vol. 3, no. 5, pp. 529-532, 2014. [Google Scholar] [Publisher Link]

[15] Sushil Kumar Himanshu, Ashish Pandey, and Prabin Shrestha, "Application of SWAT in an Indian River Basin for Modeling Runoff, Sediment and Water Balance," *Environmental Earth Sciences*, vol. 76, no. 1, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[16] Bansode Ashish, and K.A. Patil, "Estimation of Runoff by using SCS Curve Number Method and Arc GIS," *International Journal of Scientific & Engineering Research*, vol. 5, no. 7, pp. 1283-1287, 2014. [Google Scholar]

[17] Vikash Shivhare, M.K. Goel, and C.K. Singh, "Simulation of Surface Runoff for Upper Tapi Subcatchment Area (Burhanpur Watershed) Using SWAT," *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XL-8, pp. 391-397, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[18] Rokhsare Rostamian et al., "Application of a SWAT Model for Estimating Runoff and Sediment in Two Mountainous basins in Central Iran," *Hydrological Sciences Journal*, vol. 53, no. 5, pp. 977-988, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[19] Anil Kumar Lohani, *Practicing Hydrology-An Overview*, National Institute of Hydrology, pp. 1-49, 2011. [Google Scholar]

[20] K.X. Soulis, and J. D. Valiantzas, "SCS-CN Parameter Determination using Rainfall-Runoff Data in Heterogeneous Watersheds – The Two-CN System Approach," *Hydrology and Earth System Sciences*, vol. 16, no. 3, pp. 1001-1015, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[21] K. C. Abbaspour, C. A. Johnson, and M. Th. Van Genuchten, "Estimating Uncertain Flow and Transport Parameters Using a Sequential Uncertainty Fitting Procedure," *Vadose Zone Journal*, vol. 3, no. 4, pp. 1340-1352, 2004. [CrossRef] [Google Scholar] [Publisher Link]

[22] Mou Leong Tan et al., "Impacts of DEM Resolution, Source, and Resampling Technique on SWAT-Simulated Streamflow," *Applied Geography*, vol. 63, pp. 357-368, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[23] Biswajit Das et al., "Evaluation of Multisite Performance of SWAT Model in the Gomti River Basin, India," *Applied Water Science*, vol. 9, no. 5, pp. 1-10, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[24] Vishal Singh et al., "Hydrological Stream Flow Modelling on Tungabhadra Catchment: Parameterization and Uncertainty Analysis using SWAT CUP," *Current Science*, vol. 104, no. 9, pp. 1187-1199, 2013. [Google Scholar] [Publisher Link]

[25] C. Karim Abbaspour, *SWAT Calibration and Uncertainty Programs*, A User Manual, pp. 1-100, 2015. [Google Scholar]

[26] Seyed Hashem Hosseini et al., "Application of SWAT Model and SWAT-CUP Software in Simulation and Analysis of Sediment Uncertainty in Arid and Semi-Arid Watersheds (Case Study: The Zoshk–Abardeh Watershed)," *Modeling Earth Systems and Environment*, vol. 6, no. 4, pp. 2003-2013, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[27] Binod Bhatta et al., "Evaluation and Application of a SWAT Model to Assess the Climate Change Impact on the Hydrology of the Himalayan River Basin," *Catena*, vol. 181, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[28] Henok Shiferaw et al., "Modelling Hydrological Response under Climate Change Scenarios using SWAT Model: The Case of Ilala Watershed, Northern Ethiopia," *Modeling Earth Systems and Environment*, vol. 4, no. 1, pp. 437-449, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[29] P.W. Gassman et al., "The Soil and Water Assessment Tool: Historical Development, Applications, and Future Research Directions," *Transactions of the ASABE*, vol. 50, no. 4, pp. 1211-1250, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[30] M.P. Tripathi, R.K. Panda, and N.S. Raghuwanshi, "Identification and Prioritization of Critical Sub-watersheds for Soil Conservation Management using the SWAT Model," *Biosystems Engineering*, vol. 85, no. 3, pp. 365-379, 2003. [CrossRef] [Google Scholar] [Publisher Link]

[31] C. Saranya Nair, and Ashwini Mirajkar, "Integrated Watershed Development Plan for A Sub-Basin, Central India," *Water Supply*, vol. 22, no. 3, pp. 3342-3351, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[32] Hadji Dauda Smaila Kallon, Peiyue Li, and Wenhai Shi, "Development and Application of SWAT-MODFLOW in Surface Water-Groundwater Interactions: Current Status and Future Challenges," *Environmental Earth Sciences*, vol. 85, no. 2, pp. 1-24, 2026. [CrossRef] [Google Scholar] [Publisher Link]