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# Applicability of the SWAT Model in Medium-Sized River Basins of Nepal: A Case Study of East Rapti and Kankai River Basin

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***Abstract***

Hydrological modeling in data-scarce regions faces challenges that hinder effective water resource planning. Adhering to these challenges, numerous ungauged or poorly monitored basins are present in Nepal, which need a suitable methodology to address these problems. This study examines the applicability of the SWAT model in medium-sized, rain-fed perennial river systems: the East Rapti and the Kankai River Basins. Using the SUFI-2 algorithm in SWAT-CUP, calibration was performed with thirty parameters based on observations at Rajaiya (East Rapti) and Mainachuli (Kankai) station. Results showed that SWAT could replicate the hydrological response at daily scale, except the high flow events. The model performed very well at monthly scale with NSE values ranging from 0.83 to 0.94, $R^2$ from 0.86 to 0.96, and PBIAS below 15%. In both river basins, the groundwater parameter (GWQMN) was found to be most sensitive. These findings support water resources availability assessment and resource management at basin-scale.

***Keywords****—SWAT, medium-sized river, rain-fed river system, Kankai Basin, East Rapti Basin*

## 1. INTRODUCTION

Hydrologic modeling plays an important role in water resource management to analyze the resource availability and its dynamics. Among various approaches developed, the Soil and Water Assessment Tool (SWAT) is becoming increasingly popular, which relies on spatially-distributed inputs such as topographic, land-use, soil, and climate data (Krysanova and White, 2015). It is a semi-distributed hydrological model widely used for simulating river basin hydrology, especially in data-scarce regions (Marahatta et al., 2021). SWAT is a process-based model that operates on a daily time step, efficiently simulating water, sediment, and agricultural chemical yields in ungauged watersheds over long periods (Gassman et al., 2014). Developed by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS), SWAT relies on parameters—such as curve number

(CN) for runoff estimation, soil hydraulic conductivity, and evapotranspiration coefficients—to represent the physical and hydrological characteristics of a basin (Gassman et al., 2014). It has been applied globally for watershed assessments, including flood forecasting, water quality analysis, and agricultural planning. Additionally, it estimates rainfall-runoff relationships and water balance components (Devkota et al., 2024). SWAT is particularly useful for large-scale studies due to its ability to model complex hydrological processes over long periods. Prajapati et al. (2024) used SWAT in the Sunkoshi River Basin to predict hydrological flow using a 36-year record of rainfall and temperature. The model, which was used to assess the water balance equation for resource management planning, was calibrated and validated with Nash-Sutcliffe Efficiency (NSE) values of 0.82 and 0.73 monthly and daily, respectively (Prajapati et al., 2024). SWAT was also employed in the Upper Godavari Basin (UG), where rainfall variability and reservoir storage complexity posed challenges (Praveen Kumar et al., 2019). Moreover, SWAT was utilized in the Budhigandaki River Basin (BRB), a high-altitude catchment in Nepal, assisting in understanding rainfall-runoff characteristics in snow-fed basins (Marahatta et al., 2021). Another study was conducted in the Indrawati River Basin using SWAT for streamflow simulation and water resource assessment. The calibrated model was further expanded to assess the effects of hydrology on different tributaries, agricultural land, and their combination (Shakya, 2011). The SWAT modeling study in Nepal's West Seti Basin demonstrated that elevation bands significantly improved streamflow simulations (NSE=0.82) while climate projections showed 19.9% increased discharge by mid-century (2045-2069), providing critical insights for Himalayan water resource and hydropower planning (Bhatta et al., 2020). SWAT model calibration often requires optimization tools like SWAT-CUP, which incorporates SUFI-2 for sensitivity and uncertainty analysis (Praveen Kumar et al., 2019). In the Narayani River Basin, multi-site calibration was conducted using SUFI-2 to make policy regarding sustainable water utilization (Devkota et al., 2024). Additionally, most studies combine SWAT and GIS to estimate hydropower potential for sustainable hydropower development planning (Joshi and Mishra, 2024).

However, the calibration of SWAT parameters requires detailed datasets, often lacking in Nepal due to harsh terrain, limited stations, and inconsistent monitoring (Jin and Jin, 2020). Nepal has many rivers, but not enough data for modeling. For example, many hydrological records are incomplete and limited because of many reasons such as technological limitations, harsh topography, extreme weather conditions, and basin-specific conditions. The unavailability of adequate basin information, including hydrological and meteorological information, poses a challenge. Additionally, there is a study gap in medium-sized basins, which has not been explored. As mentioned earlier, there are limited hydrological and meteorological stations in the Kankai basin, which might not fully capture the spatial variability of the basin's hydrological dynamics (Sharma et al., 2025). This river system faces challenges related to flooding and water resource management, making accurate hydrological modeling essential. Therefore, this study is conducted to evaluate the applicability of the

SWAT model for this medium-sized river basin. The research question guiding this study is: Can SWAT, calibrated with hydroclimatic observations, accurately simulate hydrological processes in medium-sized, monsoon-driven basins like East Rapti and Kankai? We hypothesize that SWAT can effectively model these basins despite data limitations, offering a framework for water resource management in similar ungauged systems of Nepal.

## 2. MATERIALS AND METHODS

### 2.1 STUDY AREA

#### 2.1.1 East Rapti River Basin

The East Rapti River Basin is located in central-southern Nepal, covering approximately 3,037 km². The basin spans multiple districts, including Chitwan, Makwanpur, and Parsa, and serves as a significant hydrological unit in the region. Originating in the Mahabharat Range, the river initially flows westward before turning southward and ultimately joining the Narayani River, a major tributary of the Ganga.

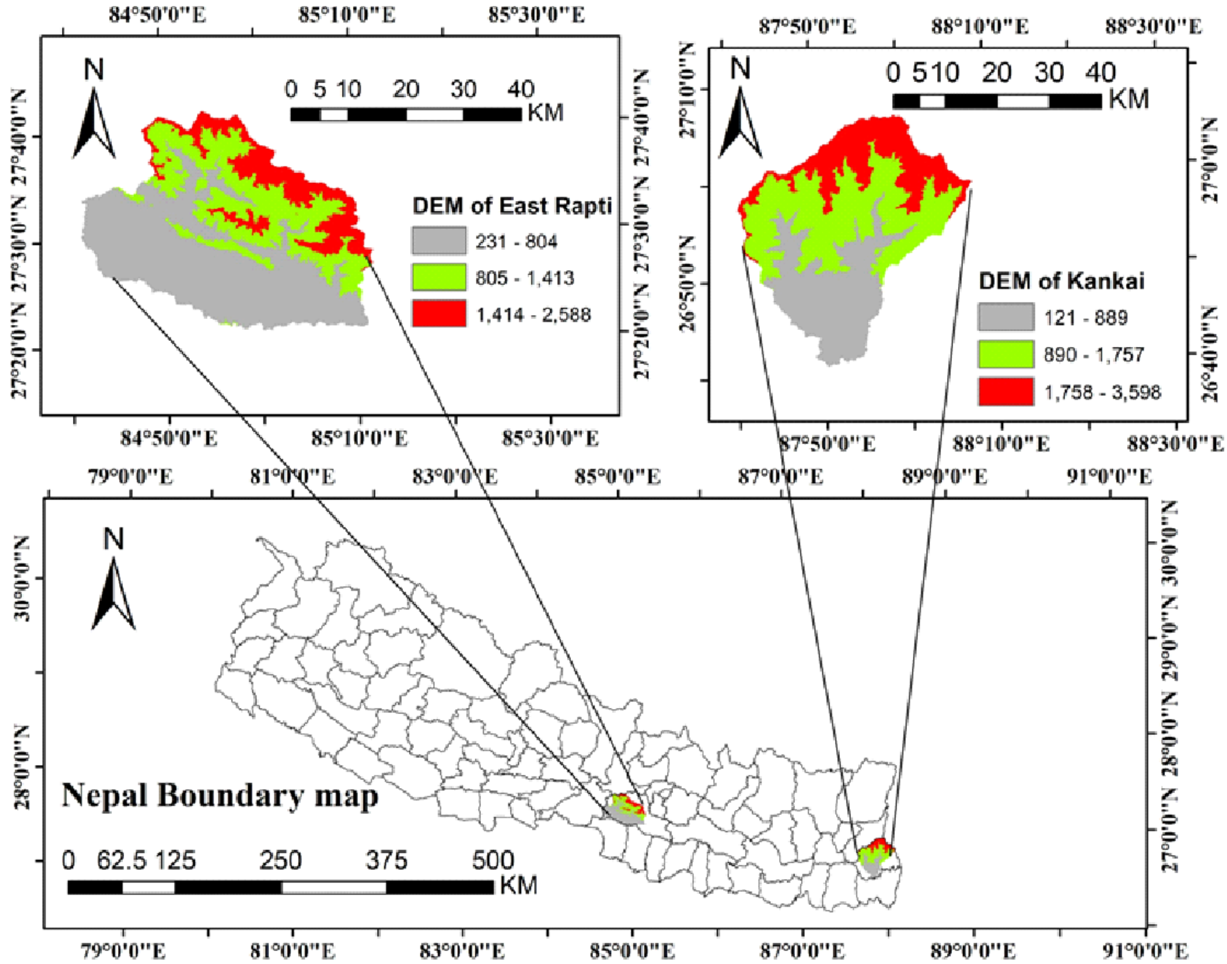


**Figure 1:** Geographic location of East Rapti and Kankai River Basins in Nepal.

The East Rapti River Basin exhibits a considerable elevation range, from over 2,500 meters in the Mahabharat hills to less than 200 meters in the Terai plains, shown in Figure 1. This topographical variation strongly influences runoff generation, sediment transport, and groundwater recharge. The steep upper catchments generate rapid surface runoff, while the lower Terai areas experience slower flows, leading to flood-prone conditions. The basin receives substantial monsoonal precipitation, with higher elevations contributing orographic rainfall and groundwater recharge. This results in a dynamic hydrological system characterized by high peak flows in the monsoon and reduced baseflow during the dry season. The East Rapti River Basin experiences a monsoon-dominated climate, with over 75% of annual precipitation occurring between June and September. Average rainfall in the basin is approximately 2,000 mm, with peak discharge observed in July and August due to intense monsoonal rainfall. In contrast, the dry season (November to May) sees significantly reduced precipitation (20 mm in winter), leading to low river flows primarily dependent on groundwater contributions. The hydrological regime is thus characterized by rapid peak flows in the monsoon and diminished baseflow in the dry season.

The map displays eight categories for LULC classification for a region, most likely Nepal: The north and centre are dominated by forests (FRST) represented by dark green, patches of grasslands (GRAS) shown by yellowish-green, and shrublands (SHRB) shown by light green. In the south, there is a lot of agricultural land (AGRL) represented by light yellow, but not much barren land (BARR) by pale yellow.  There are a few bodies of water (WATR) represented by their natural colour blue.  The urban areas (URMD) are represented by red, which seems to be concentrated in the centre, whereas the cultivated woods (CAUF, grey) are sparse, as shown in Figure 2.

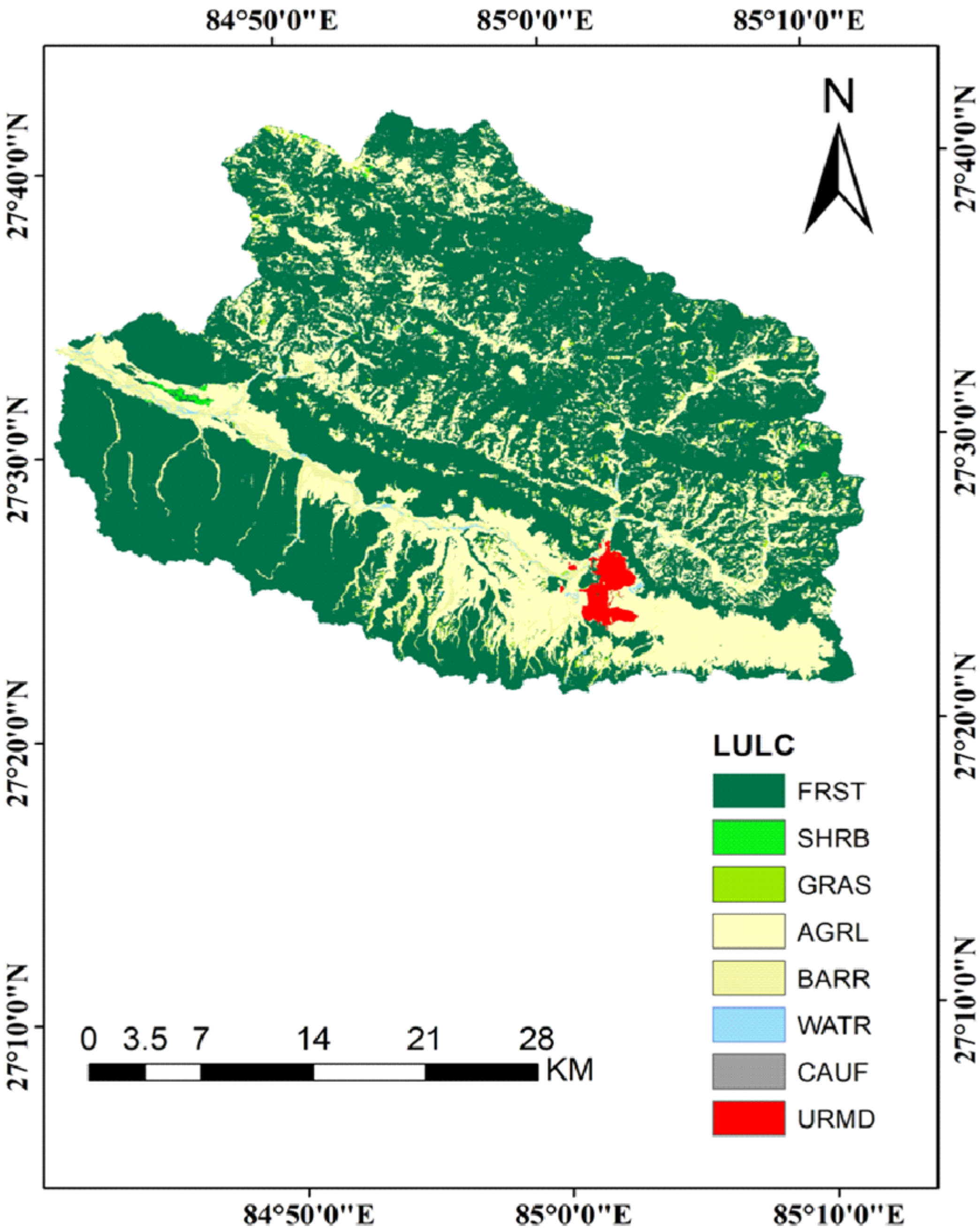


**Figure 2:** Land use/land cover distribution in the East Rapti River Basin, showing dominant agricultural and forested areas

The East Rapti River Basin in Nepal exhibits diverse soil types influenced by its varied topography. Fertile Eutric Cambisols (pink) dominate the east and north, ideal for agriculture due to good drainage and nutrient content, while Chromic Cambisols (blue) in the northeast are moderately fertile with more clay. Waterlogged Gleyic Cambisols (red) in central and southern areas hinder farming, and nutrient-poor Ferralic Cambisols (green) prevail in the southeast. Shallow Dystric Regosols (dark blue) cover rugged central and western zones, unlike fertile Haplic Phaeozems (beige) in small patches. Wet Eutric Gleysols (dark green) and scarce Orthic Luvisols (orange) complete the mix. Fertile soils support farming in flat areas, while Regosols and Gleysols in hilly or wet zones challenge cultivation, shaping land use and agricultural planning as shown in Figure 3.

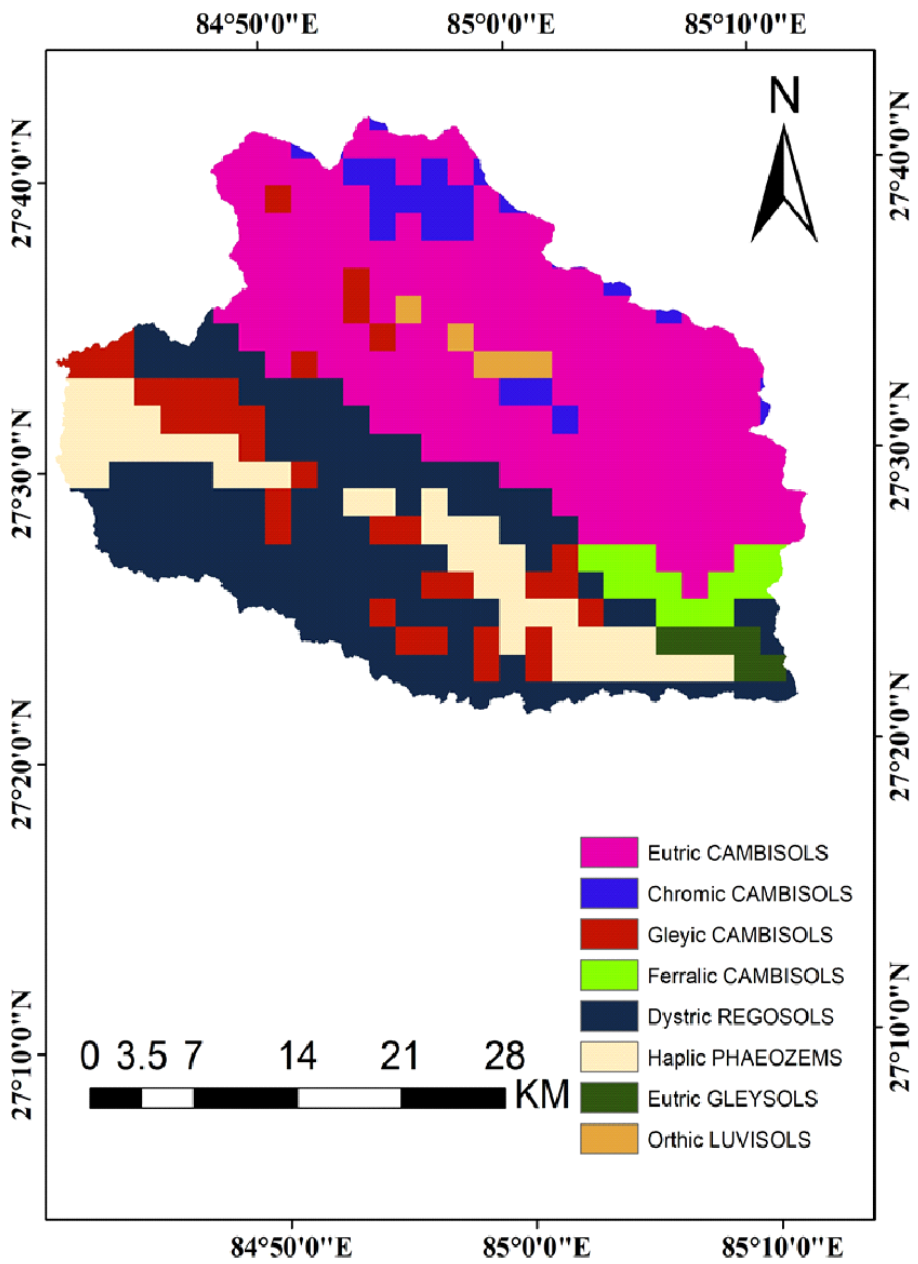


**Figure 3:** Soil Classification in the East Rapti River Basin

### 2.1.2 Kankai River Basin

The Kankai River Basin is an important hydrological system in eastern Nepal (Figure 1), covering approximately 1,172 km² across Ilam, Panchthar, and Jhapa districts. Originating in the Mahabharat Range, it flows southward through varied landscapes before joining the Mawa River, which connects to the Ganga Basin as shown in Figure 1. This basin is crucial for agriculture, groundwater recharge, and ecological stability, but faces challenges like monsoon flooding and water management. Flooding in Jhapa's lowlands is a key concern, with a 100-year flood inundating 65.5 km² (Karki and Khadka, 2020). The basin features significant elevation changes, from over 2,400 meters in the upper Mahabharat Range to about 60 meters in the flat Terai plains. These gradient influences water movement, with steep upper areas causing rapid runoff and erosion, while the lower Terai is prone to flooding due to slow drainage.

The river basin has a monsoon-dominated climate, with over 80% of its 2,200 mm annual rainfall occurring between June and September, peaking in July and August. During the dry season (November to May), rainfall drops to about 25 mm in winter, reducing streamflow, which then relies on groundwater. This seasonal variability leads to high water flows during monsoons and low flows in dry months. About 62.75% of the basin is forested, mainly in the Mahabharat and Siwalik zones, helping control runoff and erosion.

The Kankai River Basin's land cover is a mix of forests, farms, and open landscapes (Figure 4). Dense forests (dark green) cover much of the north and center, providing vital habitat and watershed protection. Farmland (light yellow) spreads across the south and central zones, forming the basin's agricultural backbone. Patches of shrubs (light green) and grasslands (yellowish-green) appear in between, often where forests transition to other uses. Bare ground is rare, and only small rivers (blue) cut through the basin. Unlike many regions, this area has almost no urban development (red) or managed forests (gray) as shown.

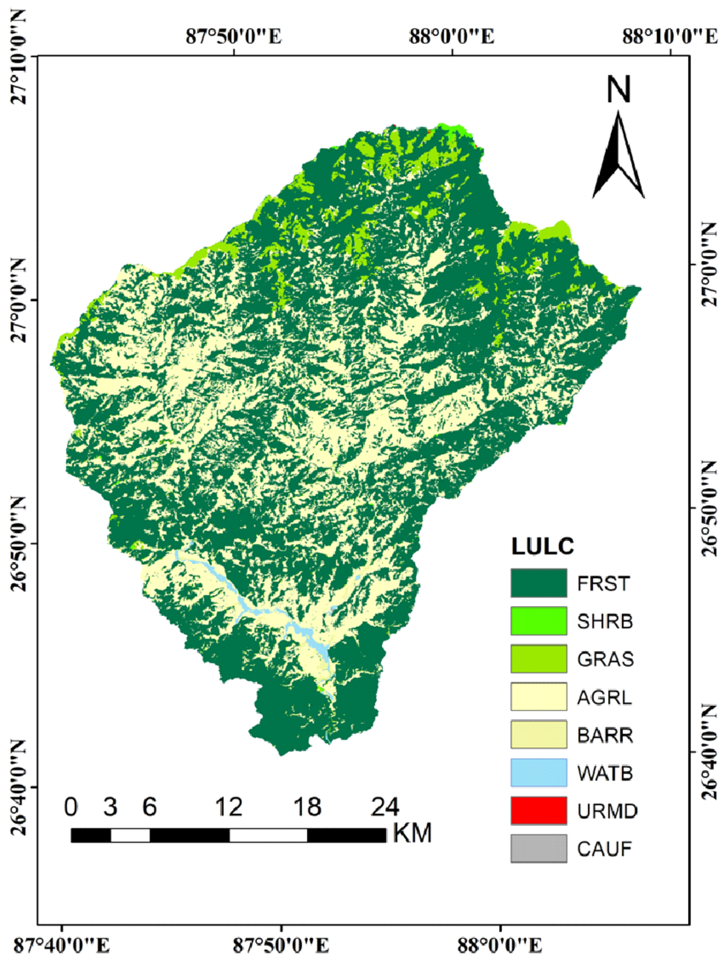


**Figure 4:** Land use/land cover distribution in the Kankai River Basin, showing dominant agricultural and forested areas.

The KRB has different soil types that affect farming in the area. Most of the northern and central parts have Chromic Cambisols (blue), clay-rich soils good for crops. The south contains Dystric Regosols (dark blue), which are thin and less fertile, found in rough landscapes. Some western areas have Eutric Cambisols (pink), well-drained soils ideal for agriculture. Central patches show Gleyic Cambisols (red), waterlogged soils that are hard to farm. A few northern spots have fertile Humic Cambisols (green) and Eutric Regosols (orange), while very small areas have rich Haplic Phaeozems (beige). Fertile soils support farming in flat zones, but poor or waterlogged soils make cultivation difficult in hilly or wet areas, as shown in Figure 5.

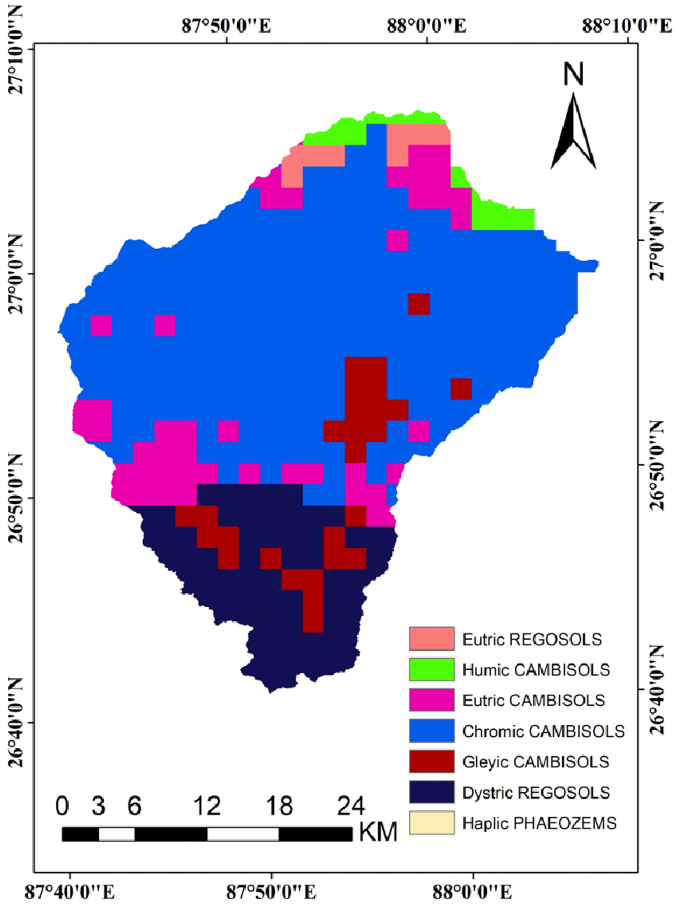


**Figure 5:** Soil Classification in the Kankai River Basin.

## 2.2 METHODOLOGY

The foundation of this study rests on comprehensive datasets spanning meteorological, hydrological, and spatial components. Figure 6 illustrates the methodology workflow, from data collection to model evaluation. Meteorological data were sourced from the Department of Hydrology and Meteorology (DHM), Nepal, covering the period from 2001 to 2015. These data include daily maximum and minimum temperatures (in °C) and daily rainfall (in mm), recorded at multiple stations across the two basins. Hydrological data, consisting of daily or monthly stream-flow records from 2001 to 2015, were also obtained from DHM. Similarly, spatial data, which are essential for the SWAT model, such as the Digital Elevation Model (DEM), land use/ land cover, and soil data, were collected from the URGS Earth Explorer platform, ICIMOD, and Nepal SOTER database.

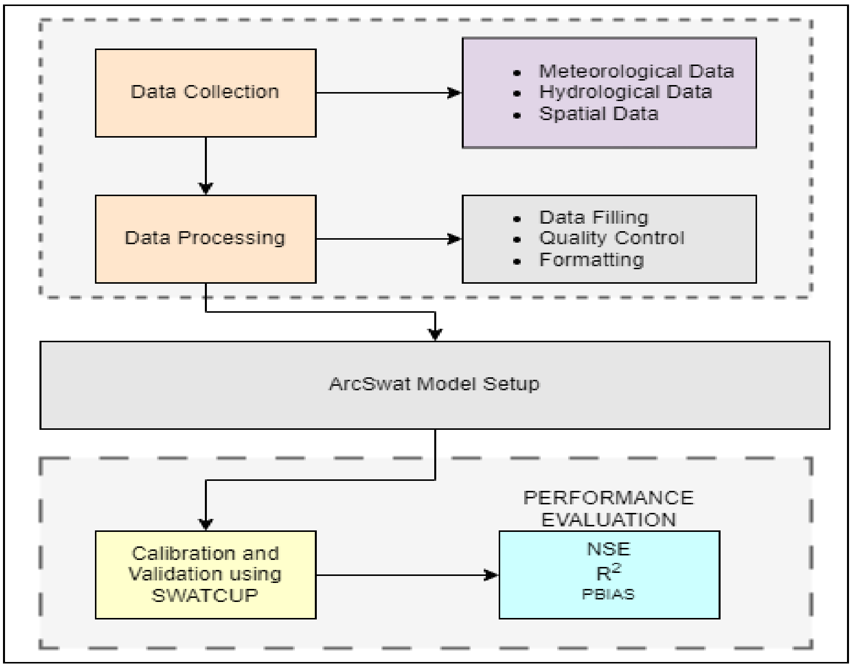


**Figure 6:** Overview of methodology applied for SWAT modeling.

Raw data required preprocessing to ensure compatibility with SWAT and SWAT-CUP inputs and to address quality issues. This includes filling missing values in meteorological and hydrological time series.

The next step includes data formatting to make it usable for SWAT modelling. For example, daily temperature and rainfall data were formatted into SWAT weather input files (.tmp and .pcp), with station coordinates and elevations specified. Similarly, streamflow data were converted to SWAT-compatible Observed Flow files, aligned with the simulation of daily time steps. Additionally, DEM, land use, and soil layers were projected to a common coordinate system (e.g., UTM Zone 44N for Nepal) and clipped to basin boundaries using ArcGIS.

### 2.3 SWAT Model Setup and Calibration

The Soil and Water Assessment Tool (SWAT) was implemented using ArcSWAT (version 2012) to simulate hydrological processes in the two basins. The setup process was consistent across East Rapti and Kankai, with adjustments for basin-specific characteristics. First, water sheds were delineated with outlets at the hydrological station location and fixing the drainage threshold area of 2000ha. Second, HRUs were created by overlaying land use, soil, and slope classes (derived from DEM). Next, a 2-year warm-up period was used to stabilize model state variables, such as soil moisture and groundwater storage, allowing the SWAT model to establish realistic initial conditions for accurate hydrological simulations (Arnold et al., 2011).

Calibration and validation were conducted using SWAT-CUP (version 5.2.1.1) with the Sequential Uncertainty Fitting (SUFI2) algorithm, focusing on stream flow simulation at gauging stations. The parameters were selected for calibration based on their sensitivity to runoff, baseflow, and channel processes. These parameters play a critical role in hydrological modeling, particularly in Nepal's unique geography with steep slopes, monsoon rainfall, and varying soil and land-use conditions. Initial ranges were set based on SWAT defaults and literature, then refined during calibration. In this study, the SWAT (Soil and Water Assessment Tool) model was calibrated using a dataset comprising 30 parameters and 1500 simulations, with the Nash-Sutcliffe efficiency (NSE) selected as the goal function to evaluate model performance. These parameters were selected based on their influence on key hydrological processes in monsoon-driven basins, as indicated in prior studies (Bhatta et al., 2020; Bista et al., 2024). The 7 years (2005-2011) were used for the calibration process. Semi-automated calibration was chosen to iteratively fine-tune SWAT parameters, allowing precise adjustments based on expert judgment and basin-specific knowledge, which automated methods might overlook due to data limitations in Nepal's complex terrain. Then the performance was evaluated using NSE, $R^2$, and PBIAS on the basis of the criteria by Moriasi et al. 2007.

**Table 1:** SWAT model performance evaluation criteria (Moriasi et al., 2007)

| **Model Evaluation** | **NSE** | **$R^2$** | **PBIAS** |
|---|---|---|---|
| Excellent | $0.75 < E_{NS} \leq 1.00$ | $0.70 < R^2 \leq 1.00$ | PBIAS ≤ ±10 |
| Good | $0.65 < E_{NS} \leq 0.75$ | $0.60 < R^2 \leq 0.70$ | ±10 < PBIAS ≤ ±15 |
| Satisfactory | $0.50 < E_{NS} \leq 0.65$ | $0.50 < R^2 \leq 0.60$ | ±15 < PBIAS ≤ ±25 |
| Unsatisfactory | $0.00 < E_{NS} \leq 0.50$ | $0.00 < R^2 \leq 0.50$ | PBIAS >± 25 |

# 3. RESULTS AND DISCUSSION

## 3.1 Model Performance Evaluation

### 3.1.1 East Rapti River Basin

Figure 7 and Figure 8 shows the comparison of observed and simulated hydrograph at daily and monthly scale, respectively. Streamflow at East Rapti (DHM Station 460: Rajaiya) has an influence of Kulekhani reservoir operating with an objective of energy generation during low flow months and/or load management throughout the year. After three cascading powerplants, water is discharged into East Rapti from Kulekhani-3 powerhouse. Incorporating design discharge (13.1 $m^3/s$) as regulated flow in the SWAT model, the model performance metrics and hydrograph (Figure 7 and Figure 8) improved, noticeably at monthly scale.

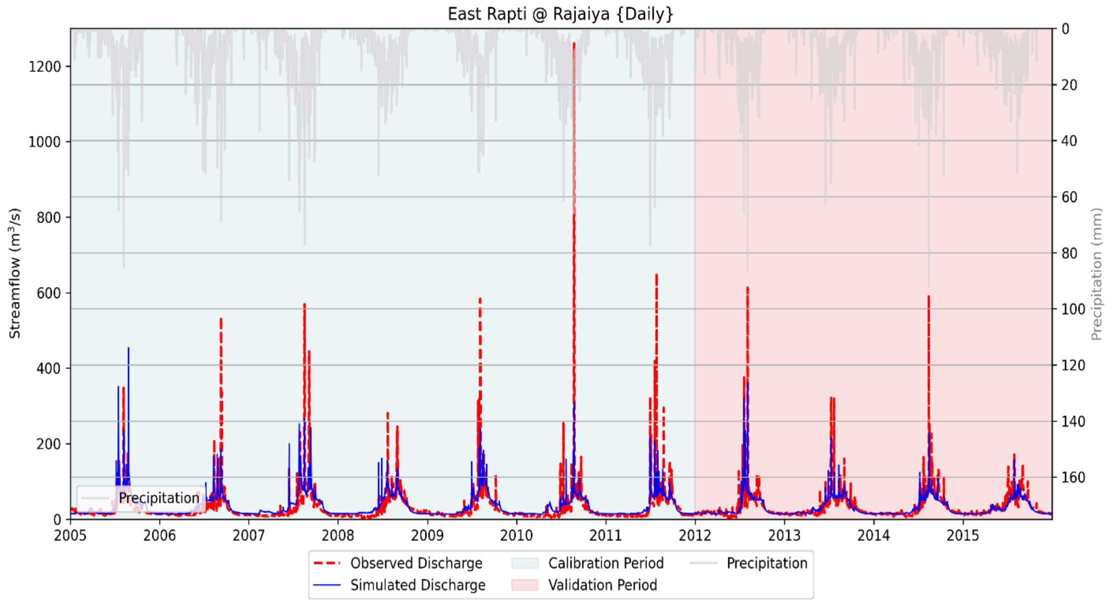


**Figure 7:** Comparison of Observed and Simulated Daily Streamflow for East Rapti River Basin

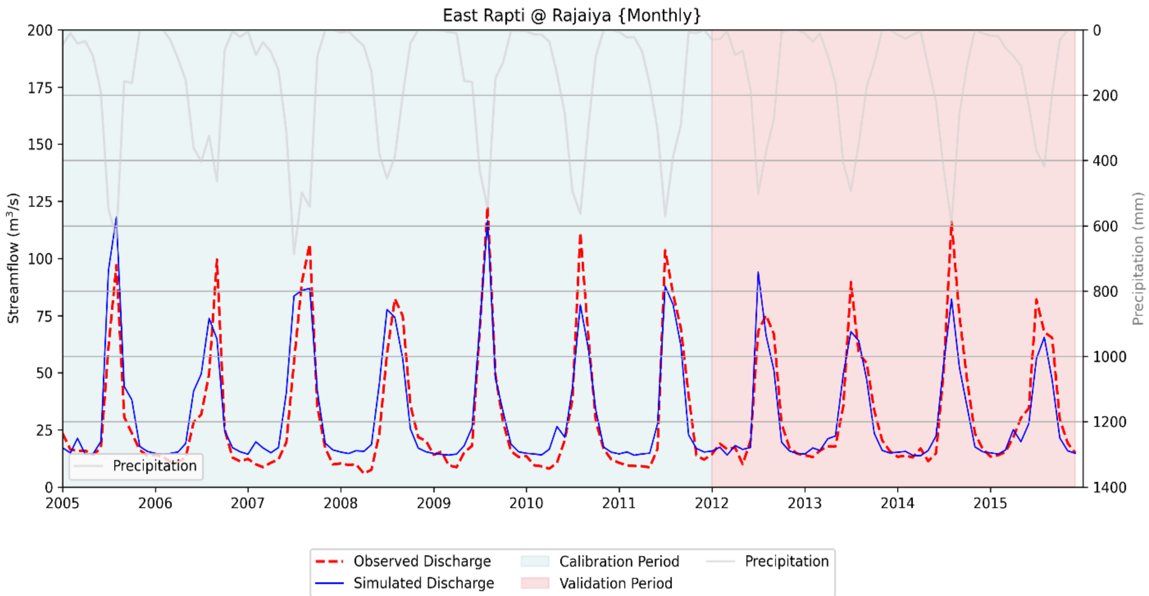


**Figure 8:** Comparison of Observed and Simulated Monthly Streamflow for East Rapti Basin

At daily scale, the performance metrics improved during validation period (Table 2). The NSE and $R^2$ greater than 0.62 indicates "good" performance based on criteria by Moriasi et al. (2007). At monthly scale, the SWAT model demonstrates a good fit during the calibration period (2005–2011), with a Nash-Sutcliffe Efficiency (NSE) of 0.85 and a coefficient of determination ($R^2$) of 0.86, indicating very good agreement between simulated and observed streamflow. NSE value exceeds the threshold of 0.85, classifying the model performance as "very good" according to Moriasi et al. (2007), while the identical $R^2$ suggests that 86% of the variance in observed data is explained by the model. The percent bias (PBIAS) of -10.75% indicates a slight overestimation of streamflow. During the validation period (2012–2015), the model maintains very good performance, with NSE at 0.83 and $R^2$ at 0.86. The PBIAS was found to be 9.3%, suggesting underpredicted flows. Overall, these metrics affirm the model's reliability for simulating hydrological processes in the East Rapti River basin.

**Table 2:** Performance metrics (NSE, $R^2$, PBIAS) for monthly SWAT simulations in the East Rapti River Basin during calibration and validation.

| | Calibration | | | Validation | | |
|---|---|---|---|---|---|---|
| | **$R^2$** | **NSE** | **PBIAS** | **$R^2$** | **NS** | **PBIAS** |
| ***SWAT ET:PM*** | | | | | | |
| U/S Diware | 0.77 | 0.75 | -15.9 | 0.77 | 0.72 | -21.1 |
| D/S Nagma | 0.77 | 0.77 | -1.2 | 0.86 | 0.84 | 8.1 |
| ***SWAT ET:HS*** | | | | | | |
| U/S Diware | 0.81 | 0.8 | -0.1 | 0.79 | 0.76 | -3.1 |
| D/S Nagma | 0.79 | 0.79 | 1.1 | 0.89 | 0.88 | 5.3 |
| | *Calibration* | | | *Validation* | | |
| | **$R^2$** | **NSE** | **PBIAS** | **$R^2$** | **NS** | **PBIAS** |
| **Daily** | 0.49 | 0.48 | -13.5 | 0.64 | 0.62 | 6.6 |
| **Monthly** | 0.86 | 0.85 | -10.75 | 0.86 | 0.83 | 9.3 |

### 3.1.2 Kankai River Basin

In case of Kankai river basin, the hydro-meteorological records are of low quality, especially the peak flow observations (like in DHM Station 795: Mainachuli). In some period, the daily streamflow observation at Mainachuli station are not in good agreement with the precipitation dataset (demonstrated by runoff coefficient > 1.6). Considering the data quality and iterative analysis of 2005-2015 timeseries in SWAT-CUP, this study finally limited the calibration-validation period from 2003 to 2005. Figure 9 and Figure 10 shows the comparison of observed and simulated hydrograph at daily and monthly scale, respectively. The rainfall-runoff response of the basin is well captured by the model at monthly scale (Figure 9). However, the model is unable to capture peak events at daily scale (Figure 10).

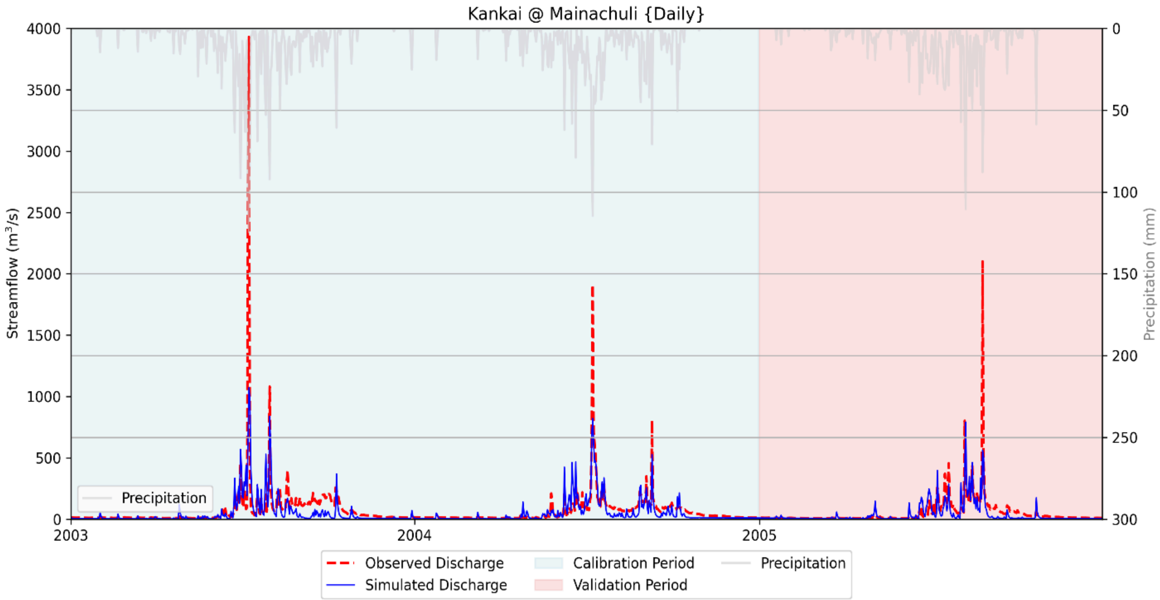


**Figure 9:** Comparison of Observed and Simulated Daily Streamflow for Kankai River Basin

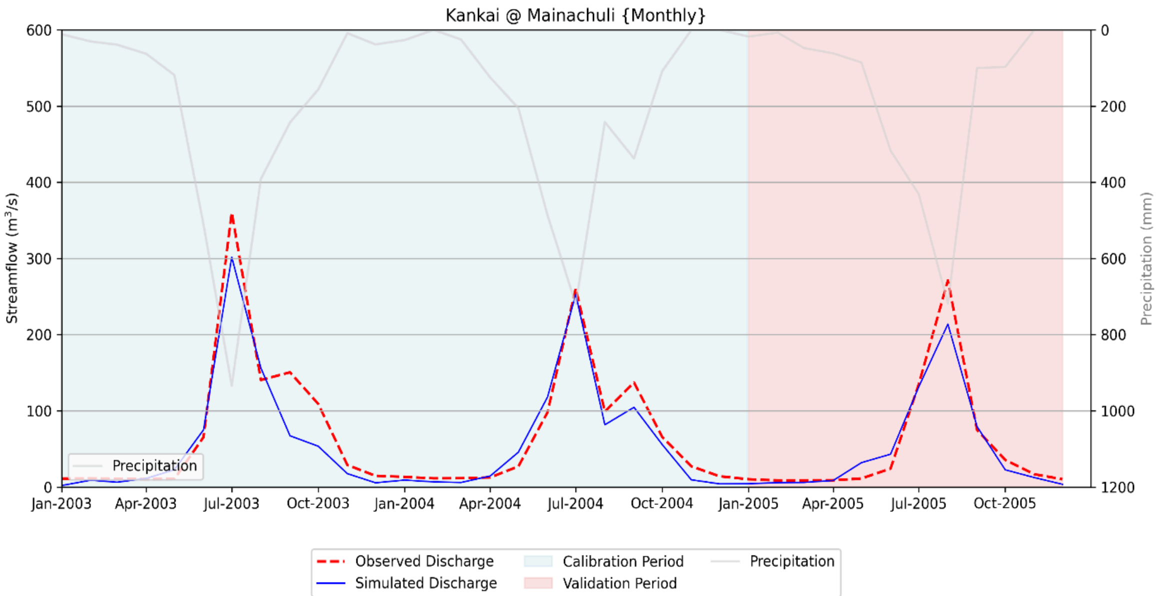


**Figure 10:** Comparison of Observed and Simulated Monthly Streamflow for Kankai River Basin

Table 3 presents the model performance metrics during calibration and validation period. At daily scale, the model achieved $R^2$ of 0.51 (Table 3) during calibration and validation period, indicating a "satisfactory" fit between simulated and observed daily streamflow, as per Moriasi et al. (2007). The PBIAS up to 29.3% indicates an underestimation of streamflow volumes. Inability to capture extreme events led to volume bias and influence performance metrics. Static parameter sets optimized for calibration may not fully adapt to evolving basin conditions during such event.

However, due to the ability to replicate hydrologic response SWAT model demonstrates the higher reliability at monthly scale analysis. Both NSE and $R^2$ greater than 0.91 denotes the “excellent” performance according to Moriasi et al. (2009). The monthly streamflow simulation estimates are reliable for both dry and wet months. For instance, the model simulation matches the observation very well for Jul in 2004 and Feb-Mar in 2005 (Figure 10).

**Table 3:** Performance metrics (NSE, $R^2$, PBIAS) for SWAT simulations in the Kankai River Basin during calibration and validation.

| | *Calibration* | | | *Validation* | | |
|---|---|---|---|---|---|---|
| | **$R^2$** | **NSE** | **PBIAS** | **$R^2$** | **NS** | **PBIAS** |
| **Daily** | 0.51 | 0.48 | 29.3 | 0.51 | 0.50 | 26.8 |
| **Monthly** | 0.93 | 0.91 | 15.6 | 0.96 | 0.94 | 8.5 |

### 3.2 Sensitivity Analysis

As part of the sensitivity analysis during SWAT-CUP, ten parameters based on p-value and with the most significant impact on model performance were selected. The top ten most sensitive parameters with fitted values for East Rapti and Kankai Basins are mentioned in Table 4. The most sensitive was GWQMN (threshold for groundwater return flow), underscoring the importance of groundwater for baseflow. Other important parameters included CN2 (SCS curve number for runoff estimation), REVAPMN (evapotranspiration out of the groundwater), and ALPHA_BNK (rate of baseflow recession). Moreover, SOL_Z (soil depth) and CH_K2 (channel conductivity) were important in Kankai. The results highlight the need for precise information on soil, groundwater, and channels in Nepal's evolving basins. This underscores groundwater’s critical role in baseflow, especially in monsoon-driven systems with significant recharge.

**Table 4:** The ten most sensitive parameters with fitted values for East Rapti and Kankai Basins, identified through SUFI-2 analysis.

| **Rank** | **East Rapti** | | **Kankai** | |
|---|---|---|---|---|
| | *Parameter* | *Fitted Value* | *Parameter* | *Fitted Value* |
| 1 | GWQMN.gw | 201.60 | GWQMN.gw | 193.32 |
| 2 | REVAPMN.gw | 233.53 | ALPHA_BNK.rte | 0.32 |
| 3 | CN2.mgt | -0.22 | REVAPMN.gw | 318.63 |
| 4 | ALPHA_BNK.rte | 0.16 | SOL_Z(..).sol | 0.81 |
| 5 | SOL_K(..).sol | -0.95 | CH_K2.rte | 109.44 |
| 6 | GW_DELAY.gw | 296.61 | GW_REVAP.gw | 0.11 |

| | | | | |
|---|---|---|---|---|
| 7 | CH_N2.rte | 0.35 | EPCO.hru | 0.03 |
| 8 | SOL_AWC(..).sol | 0.05 | ESCO.hru | 0.88 |
| 9 | SOL_Z(..).sol | 0.18 | CN2.mgt | -0.26 |
| 10 | OV_N.hru | 7.83 | GW_DELAY.gw | 222.37 |

## 4. CONCLUSIONS

This study tested the SWAT model's effectiveness in simulating hydrological processes in Nepal's medium-sized, monsoon-driven East Rapti and Kankai River Basins. Despite the data quality and model's limitation, SWAT model could replicate the hydrological response at daily scale. However, capturing the extreme event still remained a challenge and consequently influenced the performance metrics. The model achieved very good performance at monthly scale, with calibration and validation period NSE values ranging from 0.83 to 0.94, $R^2$ from 0.86 to 0.96, and PBIAS below 15%. Sensitivity analysis revealed GWQMN as the most influential parameter, highlighting groundwater's critical role in sustaining baseflow in these rain-fed systems. These findings offer policymakers a reliable tool for water resource management. SWAT's accurate streamflow predictions can guide irrigation and multiple purpose water allocation in medium sized river basin. By integrating SWAT as hydrologic modeling tools for climate adaptation plans, policymakers can ensure sustainable water management in these dynamic basins. This can be helpful in flood risk management for early warning systems and the design of check dams to manage runoff.

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