Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

SWAT-based evaluation of multi-decadal land use dynamics and hydrological response in the data-scarce Nambul River Watershed, Manipur

Rebati Sinam

rebati.sinam@dmu.ac.in

Dhanamanjuri University

Research Article

Keywords: Nambul river, SWAT Modelling, Watershed management, Runoff, Imphal, Land use land cover

Posted Date: September 24th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10881606/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Research Article

SWAT-based evaluation of multi-decadal land use dynamics and hydrological response in the data-scarce Nambul River Watershed, Manipur

Rebati Sinam [1*]

[1] Department of Geography, Dhanamanjuri University, Imphal, Manipur, India – 795001

**Corresponding Author: Rebati Sinam | Email: rebati.sinam@dmu.ac.in | ORCID: 0000-0002-3660-8144*

Abstract

Nambul river serves as the main canalised channel passing through the heart of densely populated city of Imphal, Manipur, North East India. Out of the recorded 1432 diurnal gauge heights of Nambul river between 2008 to 2021, 361 days crossed the warning level and 75 days passed the flood level, indicating that Nambul river is highly prone to annual flooding. Imphal city has been experiencing rapid peri-urban expansion and transformation of the agricultural floodplains into low-density built-up space. To assess the influences of changing urban landscape and concretisation, the Soil and Water Assessment Tool (SWAT) were used to assess the impact of land use alterations on the hydrological dynamics using land use of 2001, 2011 and 2021. The deterministic performance of the model was very good giving a Nash–Sutcliffe efficiency (NSE) of 0.78, a coefficient of determination (R^2) of 0.78, a percent bias (PBIAS) of -5.4 %, a root-mean-square error to observations standard deviation ratio (RSR) of 0.47. While the Nambul River Watershed experienced significant land use alterations, including increasing urbanization and changing forest cover pattern, the anticipated impacts on total streamflow and surface runoff were rather insignificant and subtle. The study shows that the influence of land cover change on runoff in the Nambul River Watershed is more complex than a direct, linear relationship raising the need for careful interpretation of modelling results of data scarce environment and a holistic approach to sustainable watershed management.

Keywords: Nambul river, SWAT Modelling, Watershed management, Runoff, Imphal, Land use land cover.

1 Introduction

River discharge is a dependent function of the meteorological condition, geology, soil type and the land use pattern of a region. Understanding the hydro-geomorphology of a region in the form of a watershed is significant as the streamflow, surface runoff, water availability and quality are affected by the natural or man-made phenomena happening within the watershed. It is a known fact that not all the precipitate that falls in a watershed drain out completely at the outlet. There are conducive and non-conducive factors that determine how much of the total flow will be impounded or released of the outlet. This includes magnitude and intensity of rainfall, infiltration capacity of soil, surface and sub-surface storage, slopes, surface types, etc. To understand the runoff responses to different meteorological and terrestrial scenarios is a pivotal element of efficient watershed development and sustainable management [1] Most hydrological processes are modelled and quantified through general water balance equations which acts as the fundamental to infrastructure planning [1,2]. Over the last few decades, these natural hydrological processes are under stress from anthropogenic factors mainly due to rapid land use land cover (LULC) change [3,4]. It is no gainsaying that human alterations to the natural landscape directly influences the rainfall patterns and frequency of extreme events such as floods and droughts [3,5]. Assessing and understanding such hydrological shifts are difficult, if not impossible, in ungauged or partially gauged data scarce watersheds, where non-existence of daily monitoring system creates remarkable gaps in time series data analysis [6,7]. Nambul river watershed in Manipur, North East India, exemplify a critical urbanised catchment experiencing significant stress with limited sustainable management plan [8]. Acting as the prime feeder for Loktak lake wetland, the river faces declining runoff, increased siltation from deforestation in the upstream, toxicity from the untreated human waste, domestic graywater and haphazard urban expansion [9,10]. It is imperative that such complexity of these interactions in the hilly terrains with limited data acquisition, be studied and examined through advanced mathematical and scientific modelling techniques to simulate and manage this system effectively [11,12].

Studies across the global have consistently confirms that LULC change significantly alters surface runoff, baseflow and the overall hydrological processes [3,13–17]. Prediction models suggest that climate change, compounded with land resource mismanagement, will increase global risk of both droughts and floods hazards [18,19]. Global evidence confirms the primary mechanisms of such hazards involve increased concretisation, which limits infiltration, disrupt groundwater recharge, accelerate surface runoff [20,21] and transformation of

agricultural fields into medium to low built-up environment. Successful applications of SWAT, including a large-scale, high-resolution, continental-scale model for Europe was performed to quantify blue and green water resources, crop yields, and nitrate leaching [22] and a comparative analysis across the Scandinavian and Iberian peninsulas to determine dominant hydrological processes such as snowmelt and storm runoff [23]. Regional and national assessments have been conducted across North America and Africa for evaluation freshwater availability and long-term water quality [24–26]. In Africa, SWAT has been used to analyse rainfall-runoff dynamics and investigate the critical role of baseflow in total catchment discharge within the Blue Nile Basin and Lake Tana of Ethiopia, [27] . Within the same region, SWAT simulated daily sediment routing and evaluated the impact of land management interventions to prioritise critical erosion-prone areas [28,29]. Researchers have also developed a modified saturation-excess water balance version of the model (SWAT-WB) to improve predictions of where and when runoff and landscape erosion occur [30,31].

In India, SWAT has been effectively applied to model runoff, sediment, and nutrient transport across diverse agro-climatic zones. In the Ganga River, SWAT was used to assess water availability [32], estimated sediment yield in the Budhi Gandaki Basin [4] and modelled discharge in the Umiam watershed [33], Sabarmati River Basin [34]. In the humid tropical Chaliyar River basin of Kerala, SWAT was used to simulate streamflow at multiple spatial scales, showing that larger watershed sizes introduce greater prediction uncertainty [35]. Interestingly, in Kerala, concurrent local land use maps were integrated into SWAT to assess the hydrologic impact of converting forests into rubber and agricultural plantations in the Manali river and Kurumali river catchments [36]. Within these same watersheds, sub-daily SWAT simulations using hourly rainfall data were evaluated against Geomorphological Instantaneous Unit Hydrographs (GIUH) to model single-event flood hydrographs and peak discharges [37]. SWAT modelled the sediment control effectiveness of on-stream check dams in the Banha watershed, revealing that the check dams could reduce sediment loss by over 64% [38] and evaluated more than 60 combinations of crops, tillage implements, and fertilizer applications in the Nagwan and Marol watersheds to establish effective best management plans [39,40]. Deforestation in the upper reach significantly removes the natural vegetation and ability to stabilise soil, leading to higher erosion and sediment transport [4,21,41]. These dynamic yet consistent patterns are well documented across various studies. In Indravati River Basin, model result observed how water availability shifts under different land use conditions [42].

In mountainous, karst, or poorly gauged environments, applications of SWAT have highlighted both its capabilities as well as its process limitations. Hydrological modelling and sediment transport routing in the mountainous Beheshtabad and Vanak basins of central Iran demonstrated the model's utility for conservation planning, while revealing challenges in simulating complex snowmelt processes, karst springs, and groundwater-river interactions [43]. SWAT simulations in karst-influenced watersheds in Kentucky [44] and Coastal Plain catchments in Georgia [45] captured monthly water yields but required modified parameters to accurately account for solution channels, riparian buffer routing, and surficial aquifer storage.

In the Nambul river basin, increased urbanisation was found to alter the hydraulic flow regime [12]. It is also observed that agricultural expansion in the Loktak catchment, act as a major factor for the alterations in the hydrological flow regime [9]. Other findings reiterate that the loss of riparian vegetation, wetland encroachment, high density urban growth have significantly increased the runoff coefficient, leading to more frequent flash floods in Imphal[10,46–49]. LULC-runoff modelling is not a recent phenomenon. There are various studies and methods that have evolved over the years ranging from conceptual to fully distributed frameworks, the latest being GeoAI tools and machine learning programmes. Commonly used models include that of HEC-HMS for flood hydrographs, MIKE SHE for fully distributed processes, and the Soil and Water Assessment Tool (SWAT) [6,50,51]. Data-driven models are also used as alternatives where acquisition of robust physical data is difficult [6,52]. SWAT modelling, a physically based, semi distributed, is often preferred as they have the capability to provide a comprehensive representation of hydrological processes through its Hydrological Response Unit (HRUs) engines [1,53]. Models like MIKE SHE offers higher accuracy but they require extensive and exhaustive data which are often missing in developing countries [7,54]. SWAT is thus, chosen as a best alternative for data-scarce regions owing to its computational efficiency and ability to can simulate long-term management impacts with fewer parameters than fully distributed models [20,55].

SWAT is a process-based, semi-distributed model that operates on a daily time step [11,56]. It is designed to predict how different scenarios of land management practices impacts surface outflow, sediment transport, and agricultural yields [1,57,58]. The model's main driver is the water balance equation, which tracks water movement through HRUs [2,7]. Several studies have proven SWAT as a highly suitable and an effective model for LULC assessment as it integrates spatial data on soil, land use, and topography [55,59]. The performance of SWAT in ungauged basins or partially gauged basins has been improved through the integration of

remotely sensed data, such as GLASS leaf area index (LAI) and satellite soil moisture [60,61]. Other studies on Nambul river includes that of Loktak Lake where hybrid models (e.g., MIKE SHE-SWAT) were used to simulate discharge from its nine sub-catchments including Nambul [6,9]. However, only a few limited studies have provided a systematic evaluation of how specific LULC transitions directly alter long-term runoff characteristics in the Nambul River's complex urbanized environment [9,12]. This may be attributed to data scarcity including lack of historical discharge record, soil properties, climate data and if available, the problem of missing gap persists [6]. In the Nambul River Basin, the absence of continuous gauge observations limits long-term comprehensive modelling [12]. Additionally, sub-hourly rainfall data required for accurate erosivity determination is often unavailable in Northeast India [21].

Most studies have overcome these limits by utilising remote sensing and regionalization techniques [62,63] and incorporating satellite-derived soil moisture and high-resolution DEMs [64]. However, uncertainty concerns remain, as these models can overestimate or underestimate surface runoff without substantial site-specific calibration [65,66]. While assessment on water quality and sediment loading has been explored, the impact of urban expansion on flow regime for this region remains under-quantified [6,9,12,67]. Addressing these gaps is essential for developing resilient watershed management policies and restoring the ecological health of the Nambul River.

2 Study Area

Nambul river is one of the twelve major rivers of Manipur river basin, situated in the North Eastern region of India which includes Barak, Chakpi, Imphal, Iril, Khuga, Makru, Sekmai, Wangjing, Irang, Thoubal, Tuivai. The Nambul river watershed is generated using SWAT watershed delineation tool, covers about 183.18 km², with elevations ranging from roughly 767 to 2,332 metres above mean sea level (Fig. 1). Imphal, Iril, Thoubal, Khuga, Chakpi and Nambul drain into the Loktak lake of Manipur from where it collectively flows as Manipur River, passes through Myanmar and joins Chindwin river which is the largest tributary of Myanmar’s Irrawady river. Finally, it drains into Bay of Bengal. Nambul river originates from Kangchup and Kounu hills near the foothills of Baruni Hills, which is located on the western part of Imphal Valley falling in the Imphal west and Bishnupur districts of Manipur. The hill elevation ranges between 1000 – 1600 metres above sea level. Throughout its course, Nambul is joined by several smaller streams and rivulets. In fact, Nambul river is formed by the confluence of three primary streams in the upper reaches of Kanchup hills, Abulok, Luwangli

and Singda. After this, Nambul flow southward upto Iroisemba, then turn towards eastward direction upto Ema Market from where it takes a 90-degree turn towards south and finally draining into Loktak lake. It covers an approximate distance of 55 kilometres from upper reaches till its confluence with Loktak lake. Nambul passes through the dense urban city of Imphal acting as the primary drainage. The stretch covers about 12-13 kilometres within the Imphal city. The river can be divided into two zones for the purpose of study – first, from Iroisemba to Heirangoithong (main market) where it joined by Naga Channel (4.77 km approx.) and from naga channel to Langthabal (7.64 km) where it exits the main city. It is worth mentioning that Nambul river act as the main sewage canal where more than 70 sewage canals feed into it which excessively increase the pollution and contamination of the river. This river is very important from ecological point of view as it is the main tributary that flows into the largest freshwater lake in North eastern India, also known as Loktak lake, a Ramsar wetland site. Geologically, the watershed is composed of Cretaceous limestone, belonging to Disang, Surma and Tipam rock formations. Nambul river is a perennial river, primarily fed by springs and rainwater during the monsoon season. The river banks are subjected to diverse encroached agricultural and socio-economic activities. The banks are canalised and concretised in the main city area and it is converted into crematoriums and river front gardens. There are around 54 crematoriums along the banks of the Nambul river and 37 bridges connecting the banks. Studies on its water quality and flow suggests that it is highly contaminated and polluted, exacerbated by the reduced flow owing to increasing deforestation, riparian encroachments and conversion of land into concrete landscape. Nambul River lacks a dedicated hydrometric gauging station for continuous discharge monitoring. However daily water level records are maintained by the relevant authority during the monsoon season. Based on the recorded 1432 diurnal gauge heights data of Nambul river between 2008 to 2021 collected from the flood and irrigation department, Government of Manipur, it was found that 361 days crossed the warning level and 75 days passed the flood level, indicating that Nambul river is highly prone to annual flooding (Fig. 2 & Table 1). Recent observations highlight a trend toward more frequent and severe localised extreme events, which are further aggravated by anomalous atmospheric occurrences, such as the May 2024 hailstorm event. Lack of mechanised flood control infrastructure and modernised disaster management strategies in the region frequently results in socio-economic losses, including damage to property, livestock, local commerce, and human life.

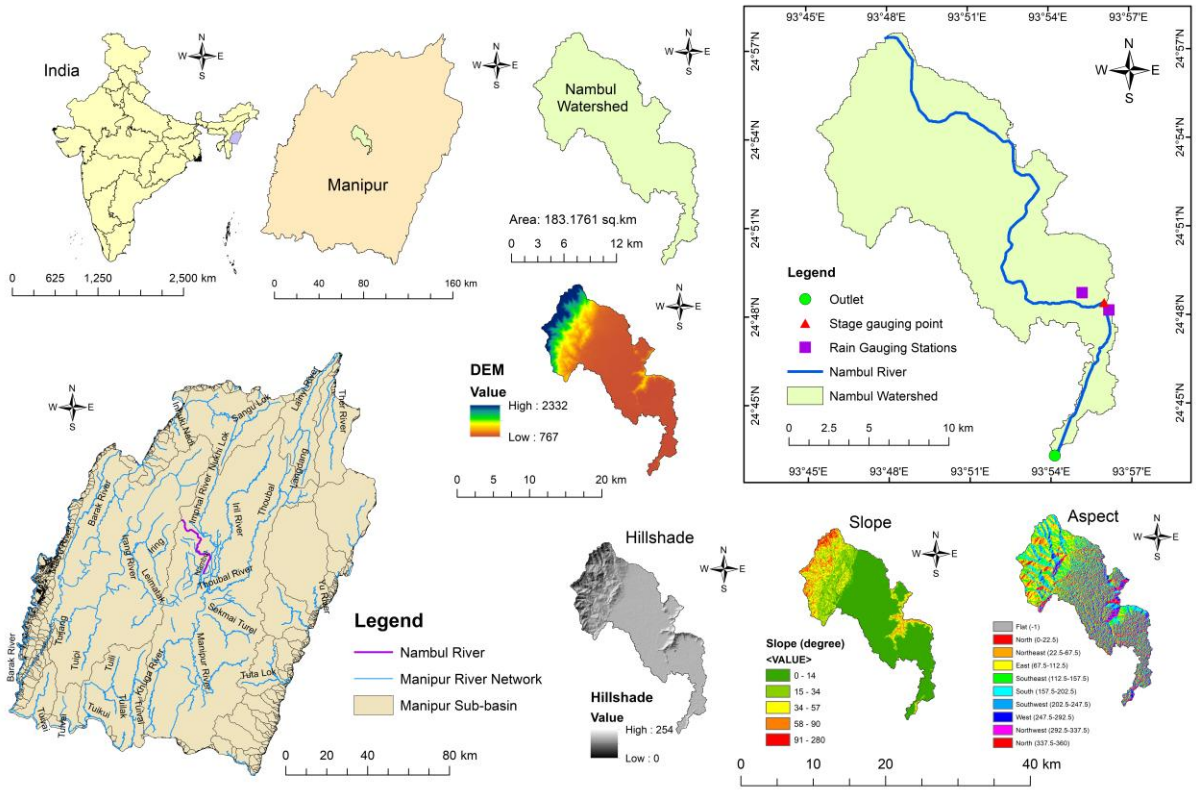


Fig. 1 Location map and topographic features of the Nambul River Watershed, Manipur, India.

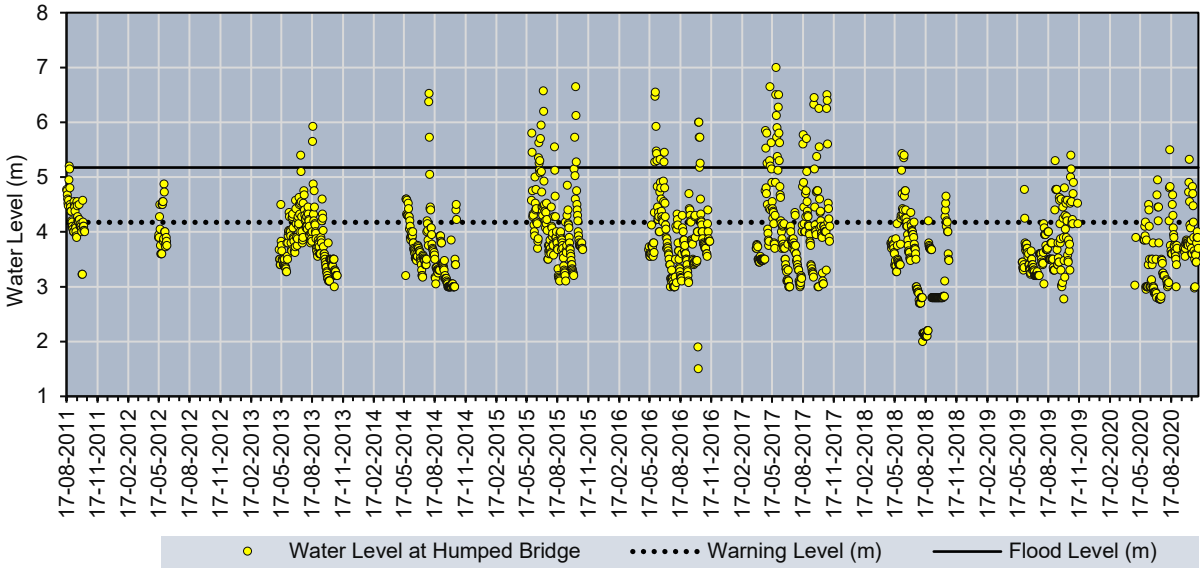


Fig. 2 Recorded diurnal water levels of the Nambul River at Humped Bridge, Imphal from August 2011 to December 2020.

3 Materials and Methods

Primary analysis of the study is based on the applicability and efficacy of SWAT modelling and supervised classification of land use land cover pattern of the study area for which a systematic approach of data collection and processing has been conducted. These steps are organised and presented below (Fig. 3).

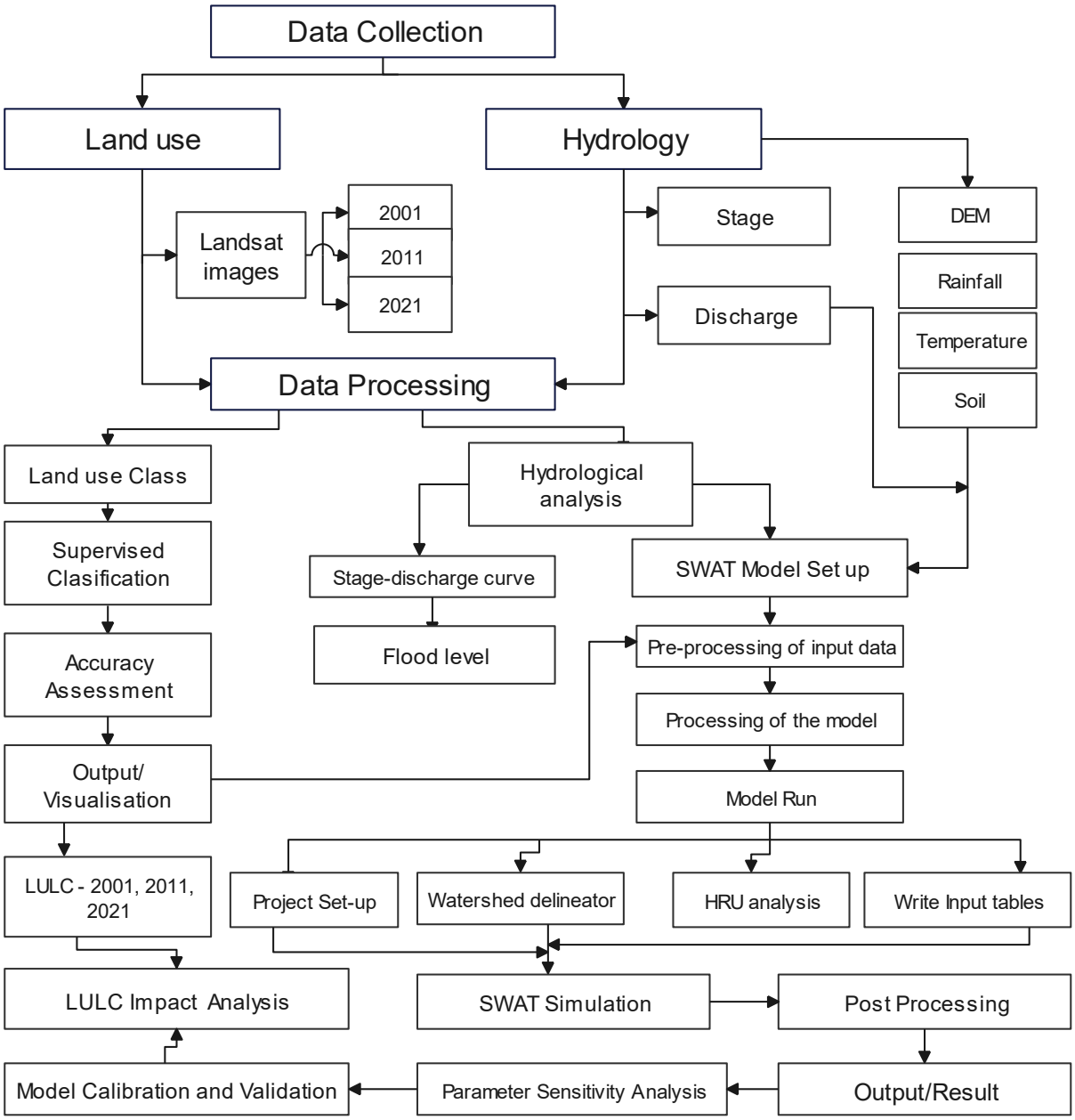


Fig. 3 Methodological framework depicting data collection, processing, SWAT model setup, calibration, and land use impact analysis for the Nambul River Watershed.

A comprehensive set of spatial and hydrometeorological data were acquired and processed for the model set up, calibration and validation. The main data collected and used in the study

include that of Landsat imagery for historical land use land cover maps using maximum likelihood (ML) supervised land use classification, Digital Elevation Model (DEM) for terrain and elevation related dataset, soil information was obtained from FAO, meteorological data, and hydrological data which includes discharge and water level data. See Table 1.

Table 1 Datasets used in the assessment of land use land cover classification and SWAT modelling of Nambul river watershed.

SN	Data type	Time Period	Sources
1	a. Rainfall Data Gridded 0.25° x 0.25° b. Daily Rainfall (Imphal Tulihal station)	1981-2020	Indian Meteorological Department (IMD), Pune, India
2	Temperature 1° x 1°	1981-2020	Indian Meteorological Department (IMD), Pune, India
3	Daily Discharge - Hiyangthang station, Nambul River	1999-2003	Loktak Development Authority (LDA), Manipur, India
4	Water level - Humped Bridge (Nambul River)	2008-2021	Flood and Irrigation Department, Public Works Department, Government of Manipur, India
5	Land Use Data	2001, 2011, 2021	Landsat Imagery, Earth Explorer https://earthexplorer.usgs.gov/
6	Soil Data	-	Food and Agricultural Organization
7	Elevation (DEM) 30 m x 30 m	-	Shuttle Radar Topography Mission, NASA

For this study, "ARCSWAT version 2012" software was installed and integrated with "ArcMap 10.5" along with SWAT Editor and SWAP Cup. Before the model run, the input data were pre-processed and classified accordingly. All the spatial input data are reprojected to "WGS_1984_UTM_Zone_46N" corresponding to UTM location of Nambul river watershed. Raster files are resampled to 30 x 30 m spatial resolution. The soil data were obtained from FAO, extracted and reclassified. Gridded daily Rainfall and daily Temperature data were used for weather input (Table 3). Solar radiation, wind speed, relative humidity used in the model run are simulated by the software.

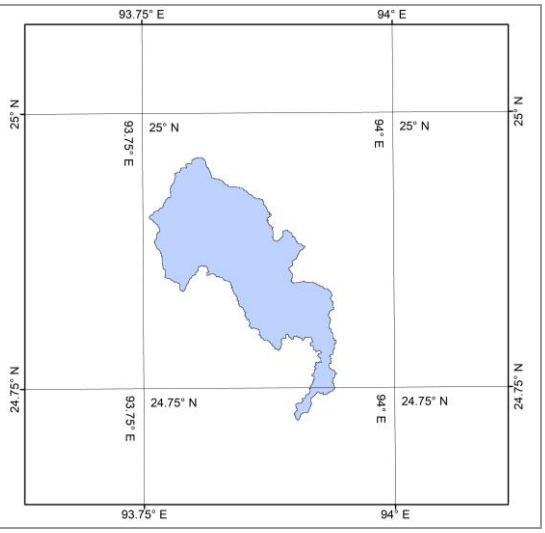
3.1 LULC Classification

LULC maps for the baseline and historical periods were derived from multi-temporal Landsat satellite imagery. Satellite data preprocessing included atmospheric, radiometric, and topographic corrections, followed by image sub-setting to extract the spatial extent of the Nambul River Watershed.

Training samples were established as Regions of Interest (ROIs) across major land classes by pairing field ground-truth observations with historical topographic maps and Google Earth imagery. Five LULC classes were identified for all study years 2001, 2011 and 2021. The classes consist of (1) water bodies & wetland, (2) built-up land, (3) cultivated area, (4) shrubs and scrubland and (5) forest & vegetation. Using these spectral signatures, a supervised Maximum Likelihood Classification (MLC) algorithm categorised the imagery based on Bayesian probability density functions. These classes were reassigned to corresponding classes as per SWAT database i.e., WATR, URHD, AGRL, FRST, FRSE respectively (Table 3).

Table 2 Gridded Rainfall and Temperature data

Rainfall Grid Point	Name	Lat	Long	Elevation (M)
1	pcp74_110	24.75	93.75	1402
2	pcp74_111	24.75	94	792
4	pcp75_110	25	93.75	1354
5	pcp75_111	25	94	828
Temperature Grid Point	**Name**	**Lat**	**Long**	**Elevation (m)**
1	tmp18_27	24.5	93.5	585
2	tmp18_28	24.5	94.5	186
3	tmp19_27	25.5	93.5	499
4	tmp19_28	25.5	94.5	1354



3.2 Accuracy Assessment of LULC classification

Map accuracy was verified post-classification by cross-referencing independent ground-truth locations using google earth images and physical visits against the generated maps. Validation points were manually selected using a stratified random sampling approach to maintain balanced representation and limited land cover classes. These reference points were structured into a confusion matrix to evaluate pixel-level alignment between mapped predictions and actual field conditions.

Map reliability was evaluated using four standard metrics:

- Overall Accuracy (OA): This shows the overall proportion of correctly classified validation sites with respect to the total sampled points:

$$\text{OA} = \left(\frac{\sum_{i=1}^{k} x_{ii}}{N}\right) \times 100$$

(where x_{ii} denotes correctly identified pixels along the matrix diagonal, N is the total reference sample size, and k represents the number of land classes).

- Producer's Accuracy (PA): This highlights classification completeness by calculating the likelihood that a real-world reference site was correctly mapped (reflecting omission errors):

$$\text{PA}_i = \left(\frac{x_{ii}}{x_{+i}}\right) \times 100$$

(where x_{+i} represents the total reference points for class i).

- User's Accuracy (UA): This examines map reliability from the user's perspective by calculating the probability that a mapped class accurately reflects actual ground conditions (reflecting commission errors):

$$\text{UA}_i = \left(\frac{x_{ii}}{x_{i+}}\right) \times 100$$

(where x_{i+} is the total mapped pixels for class i).

- Kappa Coefficient (κ): This gives the statistical agreement between map predictions and ground reference points while accounting for random chance matches:

$$\kappa = \frac{N \sum_{i=1}^{k} x_{ii} - \sum_{i=1}^{k} (x_{i+} \cdot x_{+i})}{N^2 - \sum_{i=1}^{k} (x_{i+} \cdot x_{+i})}$$

κ values exceeding 0.80 demonstrate strong classification performance, whereas scores from 0.60 to 0.80 indicate solid reliability suitable for input into hydrological models.

Table 3 Description of the type of LULC classes and corresponding code in the SWAT database

SN	Class	SWAT Database	Description
1	Waterbodies	WATR	Includes all flooded and inundated area, fisheries, domestic ponds, waterlogged farms and field, lakes and rivers and other wetlands.
2	Built-Up Land	URHD	Houses, residential colonies and other man-made concrete structures.
3	Cultivated area	AGRL	Well-drained agricultural farmland, with or without active crops
4	Shrubs and Scrubland	FRST	All area with scanty vegetation, scrubland, shrubs, barren land, fallow, current fallow, disperse forest area, open forest, mixed forest, abandoned slash-and-burn plots, etc.
5	Forest and Vegetation	FRSE	Forested area with thick tree canopy cover with +70% tree with height > 2 m.

3.3 SWAT Model setup

The methodological framework adopted for this study follows a structured sequence: watershed delineation, Hydrologic Response Unit (HRU) analysis, model calibration/validation using SWAT-CUP (SUFI-2 algorithm), and LULC scenario assessment (Fig. 3). The model project is set up and stored in the system. This is followed by watershed delineation, stream network generation and subbasin parameters calculation. For this watershed, as most of the region lies in the plain area, DEM was not able to generate the actual stream network. Because of this, the actual stream network was manually digitised using google earth and was burned to generate the drainage network for the model. For Nambul, Outlet is located at Hiyangthang (24.72°N, 93.90°E) and it covers an area of 183.18 km^2.

The watershed was delineated into multiple sub-basins using the DEM and river network. After the watershed delineation, the Hydrologic Response Units (HRUs) analysis was performed using the different combination land use data, soil data and slope class. Each sub-basin was subdivided into HRUs. Five classes of slope were created 0-5, 5-10, 10-15, 15-20, 20-9999. A threshold of 15% Land Use, 10% Soil, and 10% Slope was inputted to eliminate insignificant land areas and enhance computational efficiency while maintaining physical watershed representation. Gridded rainfall and temperature input was used for the weather input and the model was subsequently executed. Period of simulation was taken from 1st Jan. 1995 till 31st Dec. 2020 with warm up period of 4 years and model scenarios were saved. The model was executed thrice using the land use land cover data of 2001, 2011 and 2021. The

result of the model execution was stored in the “TableOut” and “TxtInOut” scenario folder. The resulting outflows are then analysed in Microsoft excel, compared and contrasted.

3.4 Parameter Sensitivity Analysis, Model Calibration and Validation:

To achieve realistic outputs following a successful model execution, sensitivity analysis of the model parameters, calibration and validation against observed data are essential [57,68–75]. Sensitivity analysis determines the rate of change in model output relative to changes in model input parameters which could be done in two ways (local and global) in SWAT CUP. Calibration involves optimizing model input parameters against observed data to minimise prediction uncertainty and achieve the closest match between simulated and actual conditions. Uncertainty analysis identifies and quantifies prediction uncertainties arising from parameter estimates, model structure, and input data during the calibration process. The final step is model validation, which evaluates the calibrated parameters against an independent observed dataset without further adjustments to the model structure.

These were executed using SWAT-CUP via the SUFI-2 algorithm. The SUFI-2 algorithm accounts for parameter uncertainty while optimizing model performance across multiple iterations. Global sensitivity analysis was executed to identify the most prominent parameters influencing the hydrologic processes within the Nambul watershed. It was evaluated using the t-stat and p-value ensuring the calibration is focused on parameters with the strongest control over streamflow. Initial parameter sensitivity analysis was conducted in SWAT-CUP using 15 hydrologic parameters across global ranges. However, it was observed that the model performance degraded relative to the baseline state. Therefore, to preserve the physically realistic representations embedded within the spatial inputs, default parameter values were retained for baseline model initialisation. Rather than employing broad parameter adjustments, calibration was executed within this default framework across multi-year historical streamflow records and evaluated. Once an acceptable fit was achieved, model validation was performed for a separate, non-overlapping observation period without altering the parameter values to verify the model’s reliability and predictive performance under independent climate conditions.

The statistical performance of the SWAT model was evaluated using standard hydrologic goodness-of-fit indicators:

a. Nash-Sutcliffe Efficiency (NSE): which quantifies the relative magnitude of the residual variance compared to the observed data variance. Values range from -∞ to 1.0,

where "NSE"=1.0 represents a perfect match, and "NSE">0.50 is generally considered satisfactory for daily or monthly streamflow modelling.

Nash-Sutcliffe Efficiency (NSE)

$$NSE=1-\frac{\sum_{i=1}^{n}(O-S)^2}{\sum_{i=1}^{n}(O-A)^2}$$

b. RSR standardizes the model's error (RMSE) by dividing it by the observed variability (standard deviation). A smaller RSR indicates less residual variation and better overall model prediction

$$RSR=\frac{RMSE}{SD}=\frac{\sqrt{\sum_{i=1}^{n}(O-S)^2}}{\sqrt{\sum_{i=1}^{n}(O-A)^2}}$$

c. Percent Bias (PBIAS): which measures the average tendency of the simulated streamflow to be larger or smaller than its observed counterpart. A "PBIAS" of 0.0% indicates optimal performance; positive values indicate model underestimation bias, while negative values indicate overestimation bias (|"PBIAS"|<15% is typically acceptable for streamflow).

$$PBIAS=\left[\frac{\sum_{i=1}^{n}(Q_{obs,i}-Q_{sim,i})}{\sum_{i=1}^{n}Q_{obs,i}}\right]\times 100$$

where

$Q_{obs,i}$ = Observed streamflow value at time step i

$Q_{sim,i}$ = Simulated streamflow value at time step i

n = Total number of paired observation time steps

d. R^2 (Coefficient of Determination) measures the strength and direction of the linear relationship between observed and simulated streamflow values. It quantifies the proportion of the variance in observed data that is explained by the model predictions. It indicates how well the trends and dynamics of the streamflow hydrograph are captured. A value closer to 1 or greater than 0.5 is considered an optimal and satisfactory model performance.

$$R^2 = \left[\frac{\sum_{i=1}^{n} \left(Q_{\text{obs},i} - \bar{Q}_{\text{obs}}\right)\left(Q_{\text{sim},i} - \bar{Q}_{\text{sim}}\right)}{\sqrt{\sum_{i=1}^{n} \left(Q_{\text{obs},i} - \bar{Q}_{\text{obs}}\right)^2} \sqrt{\sum_{i=1}^{n} \left(Q_{\text{sim},i} - \bar{Q}_{\text{sim}}\right)^2}} \right]^2$$

3.5 Evaluation of Land Use Change Effects

To evaluate the impact of land use dynamics on runoff, the model parameters were held constant and model was run repeatedly while interchanging LULC maps for the analysed three periods (2001, 2011 and 2021) corresponding to different baseline. By locking all environmental inputs and parameter values, this approach isolated the hydrologic response solely attributable to land-cover transformations such as the expansion of urban built-up areas and alterations of agricultural practices across the Nambul River Watershed.

It is to be noted that Nambul river is partially gauged, and there is a limitation of historical data. However, observed discharge data were acquired from 1999 to 2003 which were obtained during a five-year longitudinal project taken up by Loktak Development Authority, Manipur. Despite its scantiness, this dataset was used to validate the simulated data. The model underwent multiple iterations to achieve the nearest accuracy.

4 Results and Discussion

Nambul River Watershed is a hydro-ecologically vulnerable watershed in Manipur, North East India, where rapid peri-urban expansion and agricultural farmland transformation is compounded with recurrent flood risks in the main Imphal City region. Evaluating the hydrological impacts of land use alterations in a data-scarce environment such as Nambul River Watershed necessitates a robust spatial and deterministic model validation before analysing runoff responses to landscape dynamics.

4.1 Accuracy Assessment of LULC Classification

Confusion matrices were evaluated for the supervised Landsat LULC classifications of 2001, 2011, and 2021 across five classified land categories as mentioned in table 3. The result of Producer's Accuracy, User's Accuracy, Overall Accuracy (OA), and Kappa Coefficient (κ) are

detailed in Table 4. This assessment will ensure high fidelity LULC inputs for SWAT model set up.

Table 4 Confusion matrix summary and accuracy classification metrics for Nambul River Watershed (2001, 2011, and 2021).

Year	Producer's accuracy					User's Accuracy					OA	κ
	WB	BU	CA	SS	FV	WB	BU	CA	SS	FV		
2001	90.00	92.16	98.25	100.00	96.30	95	98	96.55	87.50	96.30	95.45	0.94
2011	90.00	97.18	100.00	87.88	100.00	95	99	96.72	96.67	88.00	96.10	0.95
2021	77.27	93.18	100.00	76.92	77.42	100	100	86.89	66.67	88.89	88.07	0.85

* Water Bodies (WB), Built-up Land (BU), Cultivated Area (CA), Shrubs and Scrubland (SS), and Forest and Vegetation (FV).

The accuracy assessment result shows an overall accuracy of 95.45% (κ = 0.94) in 2001, 96.10% (κ = 0.95) in 2011, and 88.07% (κ = 0.85) in 2021. This observation shows a good classification of the land use classes as per remote sensing evaluation guidelines [76,77] which states that an overall accuracy exceeding 85% and a Kappa statistic above 0.80 indicate an excellent agreement between mapped land use classes and ground truth data. Although minor spectral confusion occurred in 2021 between low-density urban stretches and fallow land (User's Accuracy for Scrubland as 66.67%), the baseline spatial structures remain highly reliable for hydrological HRU definition.

4.2 Decadal Land Use Land Cover Dynamics (2001-2021)

Spatial and temporal analysis of the land use classes over the two decadal periods shows notable areal transformation between the classes – built-up, cropland, scrubland and forested region in the Nambul River Watershed. Table 5 presents the area and proportional net changes across 2001, 2011, and 2021 LULC classes. This change has been compared with other studies and report released by Forest Survey of India for the three years 2001, 2011 and 2021. According to Reimeingam (2017) [78], “Forest covers shows a gradual improvement in the state from below 17000 to over 17000 km from 2001 to 2011 despite wide practice of shifting cultivation in the hills”. The change in forest cover in the watershed is in conformity to the result of the present study [79].

Table 5 Land Use Land Cover change trends in Nambul River Watershed (2001–2021).

LULC Class	2001		2011		2021		Change (%)		
	km^2	%	km^2	%	km^2	%	2001-2011	2011-2021	2001-2021

1	Waterbodies	2.57	1.41	3.24	1.77	3.87	2.11	26.07	19.44	50.58
2	Built-Up Land	31.77	17.35	34.49	18.83	36.75	20.06	8.56	6.55	15.67
3	Cultivated area	72.42	39.53	71	38.76	67.13	36.65	-1.96	-5.45	-7.3
4	Shrubs and Scrubland	41.21	22.5	34.21	18.67	51.02	27.86	-16.98	49.13	23.8
5	Forest and Vegetation	35.2	19.22	40.24	21.97	24.39	13.32	14.31	-39.38	-30.71
	Total	183.2	100	183.2	100	183.2	100			

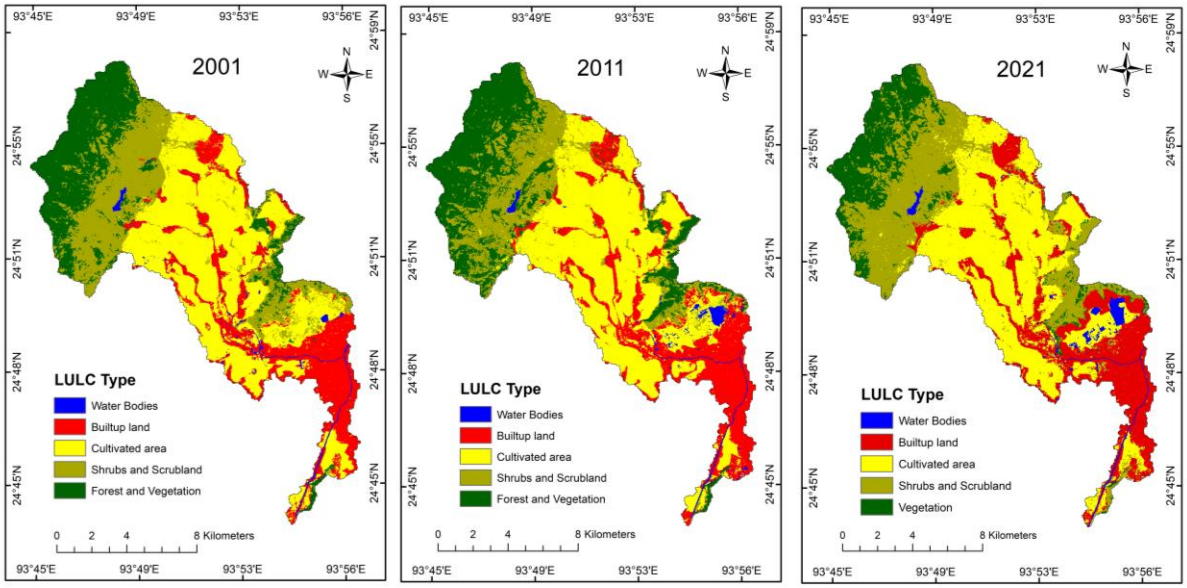


Fig. 5 Spatial distribution of Land Use and Land Cover (LULC) classes in the Nambul River Watershed for the years 2001, 2011, and 2021.

The net change from 2001 to 2011 analysis showed that waterbodies and wetland have net positive gain 26.07%, built-up land has a net gain of 8.56% and dense forest has a gain of 14.31%. Shrubs and Scrubland have the highest net loss by a proportion of 16.98% followed by cultivated area of 1.96%. The loss in waterbodies and wetland is due to conversion to built-up land while it gains area from cropland and, shrubs and scrubland respectively. Built-up land experiences gain from all classes where the majority of the gain is contributed by cropland and Shrubs and Scrubland followed by waterbodies and wetland (Fig. 5).

From 2011 to 2021, waterbodies and wetland experience a net gain of 19.44% and cultivated area examine a net loss of 5.45%. Forest and vegetation also experience a net loss by 39.38% while Shrubs and Scrubland witnessed a net gain of 49.13% and built-up region continues to grow by 6.55%. The overall two decadal land use transformations from 2001 to 2021 observed that waterbodies and wetland increased by half (50.58%) from the previous 2001 figures. Built-

up and Scrubland grows by 15.67% and 23.8 respectively over the two decades whereas Forest has the maximum loss of 30.71% followed by cropland with 7.3% loss. It is to be noted that these net gain and net loss is attributed to interclass conversion where most of the dense forest are converted to mixed forest and scrubland, while the cropland are converted either to built-up land or inundated area.

Manipur has a population of 2,84,465 in 1901, 5,77,635 in 1951, 22,93,896 in 2001 and 28,55,794 in 2011 as per Indian Census Report[1]. The population is doubled from 1901 to 1951, quadrupled from 1951 to 2001 indicating that there is a rapid increase in population since 1951. The decadal growth rate in 2001 and 2011 is 24.86% and 24.5% respectively. Due to the rapid process of urbanization and peri urban expansion, the concretisation increased in the valley. In 1951, the urban population of Manipur is only 0.49% as compared to national average of 17.29%. Now in 2011, urban population soars to 35.45% as compared to national average of 31.16% which shows that Manipur experiences a rapid growth of urbanization[80]. The number of towns in 1951 is only one which has increased to 51 in 2011. However, the growth of urbanization is primarily concentrated in the central valley specially in the four districts (Imphal West, Imphal east, Bishnupur and Thoubal). The urbanization rate of Imphal West is 55.55% in 2001, 66.33% in 2011 while Imphal east has 27.43% (2001) and 59.83% (2011). This shows that Imphal east witness a doubling of urban population from 2001 to 2011. This trend in urban built-up is expected to further increase in the coming decades. The Nambul River watershed lies within Imphal West district and part of Imphal East. Google Earth Image comparison shows visible changes in concretization of the valley during 2009 and 2021 as shown in fig. 6. As observed in the LULC classification, there is a steady increase in the areal extent of built-up land. Most of the built-up land conversion is due to transformation of cultivated area and scrubland into built-up land.

[1] The statistical information and figures is retrieved from Census of India (Office of the Registrar General & Census Commissioner, India, Ministry of Home Affairs, Government of India), 1901, 1951, 2001 and 2011; Directorate of Economics & Statistics, Manipur.

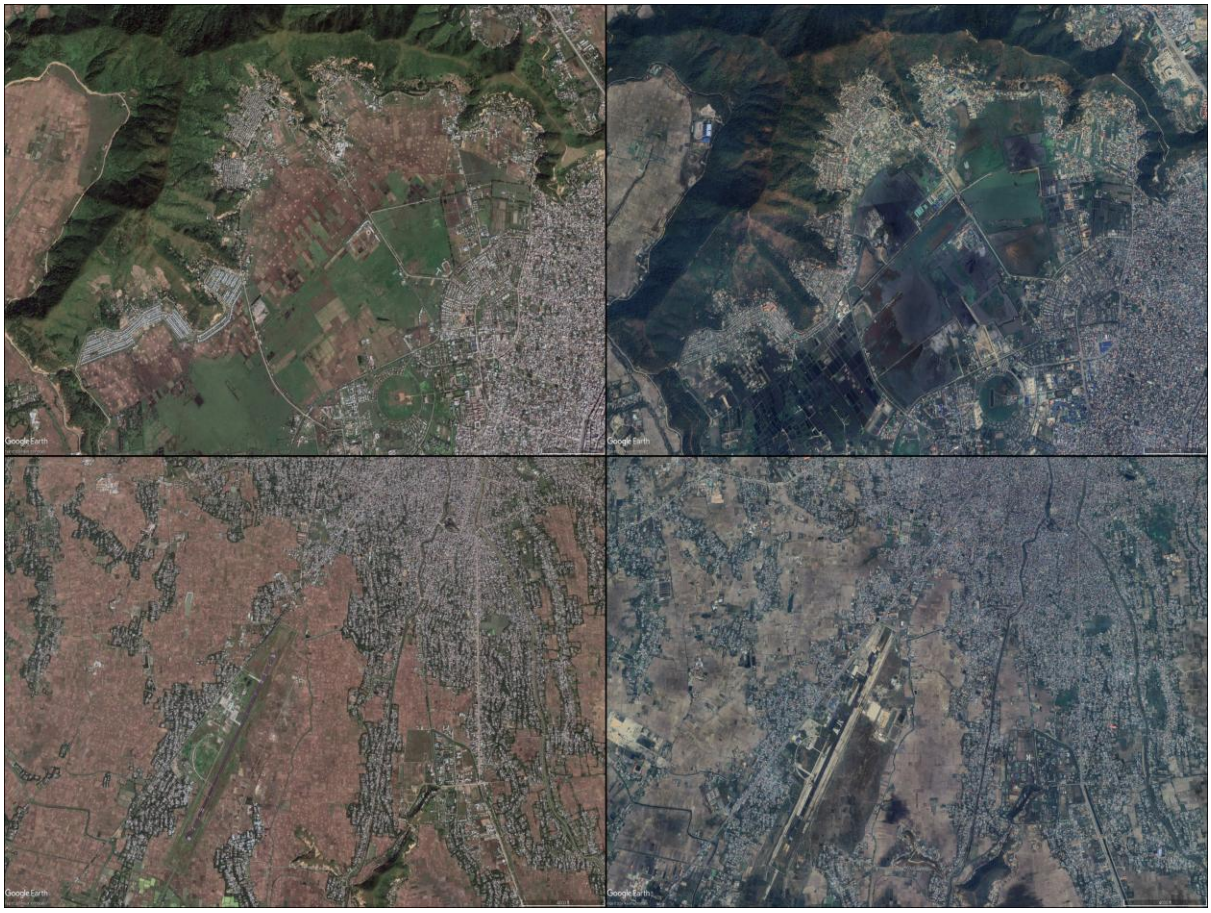


Fig. 6 Fig. 6 High-resolution satellite imagery comparison illustrating peri-urban expansion and floodplain conversion in the Nambul River Watershed: (a) Lamphel area in November 2009 (top-left); (b) Lamphel area in March 2025 (top-right); (c) Imphal Airport region in November 2009 (bottom-left); and (d) Imphal Airport region in March 2025 (bottom-right). (Map data © Google Earth, Maxar Technologies, Airbus, used under Google General Geo Guidelines).

From this spatio-temporal analysis of the LULC, it is evident that there are three primary landscape transition trends between built-up, cropland and forest. Built-up land expanded monotonically from 31.77 km² (17.35%) in 2001 to 34.49 km² (18.83%) in 2011, reaching 36.75 km² (20.06%) by 2021 representing an overall increase of 15.67% over the baseline. Urban growth was heavily concentrated as linear ribbon development along primary transport routes and Nambul river bank flowing into Imphal city. Cultivated area progressively decreased from 72.42 km² (39.53%) in 2001 to 67.13 km² (36.65%) in 2021, giving a net reduction of 7.29%. This shows that the agricultural farmlands surrounding Imphal within the watershed were systematically fragmented and converted into low-density residential structures. Dense forest initially increased from 35.20 km² (19.22%) in 2001 to 40.24 km² (21.97%) in 2011 due to local regeneration, but sharply declined to 24.39 km² (13.32%) by 2021 showing a net degradation of 30.70%. Consequently, scrubland and degraded mixed forest expanded to 51.02 km² (27.86%) in 2021.

4.3 Hydrological Model Calibration and Validation Performance

Nambul River Watershed is a data-scarce catchment and acquiring a consistent and robust historical discharge data is difficult. However, available daily discharge data spanning from 1999 to 2003 were used for model setup and performance evaluation. Default SWAT hydrological parameterisations were retained to model baseline streamflow across this observation period. Model performance was tested and evaluated using four objective functions [57,81] i.e., NSE, R^2, RMSE- RSR, and PBIAS as tabulated in Table 6.

Table 6 SWAT Hydrological model evaluation statistics for Nambul River Watershed.

Watershed	Objective Function / Metric	Value	Performance Category
Nambul Watershed	Nash-Sutcliffe Efficiency (NSE)	0.78	Very Good
	Coefficient of Determination (R^2)	0.78	Very Good
	RMSE-SD Ratio (RSR)	0.47	Very Good
	Percent Bias (PBIAS)	-5.4%	Very Good

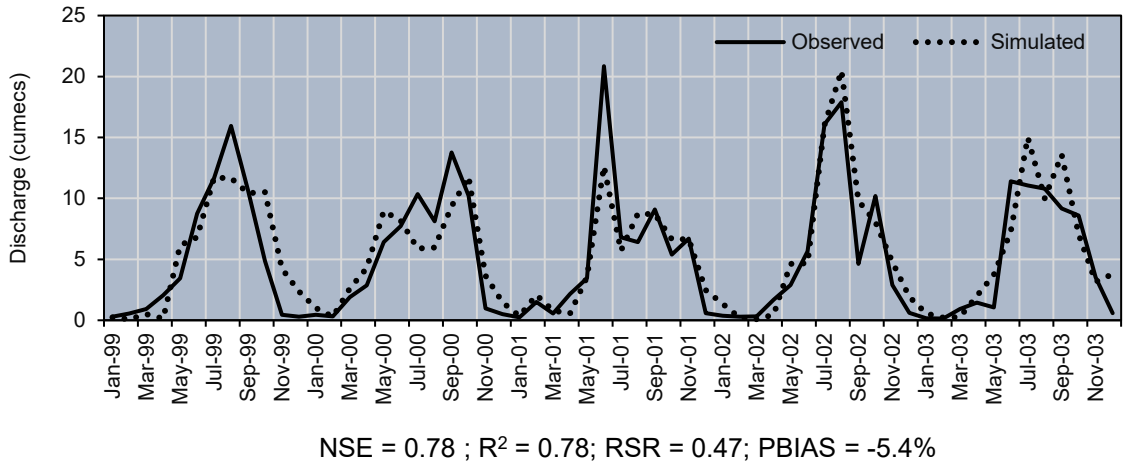


Fig. 7 Comparison of monthly observed and SWAT-simulated average streamflow (cumecs) for the Nambul River in Imphal Watershed from January 1999 to December 2003.

The statistical metrics obtained for Nambul River Watershed (NSE = 0.78, R^2 = 0.78, RSR = 0.47, and PBIAS = -5.4%) along with p-value of 0.15, indicated strong performance across all evaluation benchmarks [81]. An NSE of 0.74 indicates good predictive capability, while a low positive PBIAS of -5.4% reflects minimal streamflow underestimation. These evaluation statistics confirm that the SWAT setup for the given watershed is robust and suitable for

assessing runoff responses under various land use scenarios in the Nambul river catchment (Fig.7).

4.4 Impact of historical LULC shifts on discharge and surface runoff dynamics

To assess the impact of the hydrological influence of land cover dynamics, SWAT simulations for a period of 21 years (1999–2020) were executed by keeping all terrestrial and meteorological forcing inputs constant while interchanging the land use maps (2001, 2011, and 2021) in each model run. Streamflow responses were quantified and examined at long-term average discharge as given in table 7.

Table 7 Long-term average simulated discharge response of Nambul River under historical LULC baseline scenarios (1999–2020).

Hydrological Component	2001 LULC (baseline)	2011 LULC	Change vs. 2001 (%)	2021 LULC	Change vs. 2001 (%)
Mean annual discharge (m^3/s) – long-term average (1999–2020)	6.303	6.298	-0.08%	6.264	-0.62%

It is generally expected that urbanization and deforestation produce sharp increases in total water yield [82,83]. Interestingly, the long-term mean annual discharge of the Nambul River produced consistent amount of stream outflows across all three land use states: 6.303 m^3/s in 2001, 6.298 m^3/s (-0.08%) in 2011, and 6.264 m^3/s (-0.62%) in 2021. This relative variation (<1%) falls well within model output uncertainty and confirms that total annual discharge volume is perhaps controlled by inter-annual climatic drivers rather than broad LULC changes. This can be attributed to the dominance of intense monsoon rainfall and steep topography in driving saturation-excess runoff, which overshadows incremental imperviousness or forest alterations. This is consistent with findings in other monsoon-dominated hilly watersheds, where basin-scale hydrological responses remain muted unless LULC conversion is extreme or spatially concentrated. The annual breakdown of simulated river flow (1999-2020) across 2001, 2011, and 2021 land cover maps is presented in Table 8.

Table 8 Annual simulated surface runoff (mm/year) of the Nambul River Watershed (1999–2020) under 2001, 2011, and 2021 LULC scenarios.

Simulation Year	2001 LULC (mm/year)	2011 LULC (mm/year)	2021 LULC (mm/year)
1999	64.98	64.90	64.45
2000	63.44	63.40	63.10

2001	59.00	58.87	58.69
2002	72.55	72.51	72.22
2003	66.73	66.67	66.32
2004	101.17	101.09	100.61
2005	73.52	73.44	73.19
2006	73.95	74.00	73.37
2007	105.44	105.29	105.06
2008	109.79	109.69	109.46
2009	39.88	39.90	39.28
2010	77.70	77.61	77.30
2011	128.85	128.78	128.60
2012	133.58	133.54	133.07
2013	74.42	74.42	73.81
2014	43.86	43.77	43.29
2015	62.64	62.56	62.04
2016	72.26	72.16	71.66
2017	103.26	103.13	102.78
2018	53.79	53.83	53.26
2019	26.56	26.47	26.04
2020	48.62	48.56	48.10
Mean	*75.27*	*75.21*	*74.80*

These findings reinforce the inverse relationship between dense canopy cover and direct surface runoff generation, albeit subtle. Intact forest canopy enhances canopy interception, evapotranspiration, and root-zone infiltration. This promotes subsurface water storage, lateral sub-surface flow, percolation to shallow aquifers, and sustained return flow during dry periods. The shift from dense forest to degraded scrubland and built-up land reduces basin surface retention. Although total annual discharge remains stable, surface runoff concentration accelerates during high-intensity monsoonal storms explaining why Imphal city regularly experiences severe localized flash flooding (361 warning days and 75 flood level exceedances between 2008–2021) even under subtle total streamflow changes.

5 Conclusion

This study evaluated the hydrological impacts of decadal Land Use Land Cover (LULC) changes (2001–2021) in the data scarce Nambul River Watershed, Manipur, using the SWAT model paired with default physical parameterization. Parameter transfer through regionalisation indicated robust deterministic model performance (NSE = 0.78, R^2 = 0.78, RSR = 0.47, PBIAS = -5.4%), proving that physical hydrological modelling can be successfully applied to ungauged watersheds in North-East India. While built-up expansion (+15.67%) and

dense forest degradation (-30.71%) occurred between 2001 and 2021, the overall impact on long-term mean annual discharge was minimal (-0.62%). The relationship between land cover change and catchment runoff in the Nambul basin is non-linear and governed by complex interactions between vegetation retention, slope, and inter-annual climate variability. The recurrence of urban flooding in Imphal City is primarily driven by localised runoff acceleration, channel canalisation, and peri-urban flood-plain encroachment rather than macro-scale water yield increases. Sustainable watershed management requires integrated floodplain restoration, low-impact urban drainage, and high-altitude forest conservation. While the Nambul River Watershed experienced significant land use altercations, including increasing urbanization and changing forest cover pattern, the anticipated impacts on total streamflow and surface runoff were rather insignificant and subtle. The study shows that the influence of land cover change on runoff in the Nambul River Watershed is more complex than a direct, linear relationship raising the need for careful interpretation of modelling results of data scarce environment and a holistic approach to sustainable watershed management.

Acknowledgments

The author expresses sincere gratitude to Dr. Sachidanand Kumar for his support with data processing in R and MATLAB and guidance on SWAT tutorials, Dr. Vicky Anand for technical support during SWAT setup, Loktak Development Authority (LDA), Manipur for the provision of discharge data and Dr. Khwairakpam Eliza for her assistance with data acquisition. Special thanks are also extended to Prof. Milap Chand Sharma, Jawaharlal Nehru University, New Delhi for his continuous support and encouragement throughout this work.

Statements and Declarations

Author Contributions: The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

Funding: This work was supported by the University Grants Commission (UGC), India, through a Junior Research Fellowship (JRF) awarded to Rebati Sinam during 2015-2020. The author acknowledges the Jawaharlal Nehru University for providing computational and research facilities.

Data Availability: The datasets utilised during the current study were obtained from the following publicly available and institutional sources:

1. Digital Elevation Model (DEM): Shuttle Radar Topography Mission (SRTM) data provided by NASA, accessible via USGS Earth Explorer https://earthexplorer.usgs.gov/
2. Digital Soil Data: Harmonized World Soil Database (HWSD) provided by the Food and Agriculture Organization (FAO), accessible via (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/) or SWAT Texas A&M repository for India dataset https://swat.tamu.edu/data/india-dataset/ (Select: soil_HWSD_FAO)
3. Satellite Imagery for LULC: Landsat imagery provided by the U.S. Geological Survey, accessible via USGS EarthExplorer https://earthexplorer.usgs.gov/
4. Meteorological Data: High-resolution gridded rainfall and temperature data provided by the India Meteorological Department (IMD), Pune
   Rainfall:https://imdpune.gov.in/cmpg/Griddata/Rainfall_25_NetCDF.html
   Temperature: https://imdpune.gov.in/cmpg/Griddata/Max_1_Bin.html
5. Daily Discharge Data provided by the Loktak Development Authority (LDA), Government of Manipur, India but restrictions apply to the availability of these data, which were obtained through official permission for the current study and so are not publicly available.

All processed data generated during this study are available from the corresponding author upon reasonable request.

Competing Interests: The authors have no relevant financial or non-financial interests to disclose.

Code Availability: Data processing, spatial extraction, and analysis were executed using MATLAB and R programming environments. The R routines generated for processing the IMD gridded meteorological data are available from the corresponding author on reasonable request.

Ethical Approval: Not applicable. This study does not involve human subjects or vertebrate animals.

Consent to Publish declaration: Not applicable.

Consent to Participate declaration: Not applicable.

References

1. Wandre SS, Rank HD, Shinde VB. Calibration and validation of the SWAT model for the Sani River basin, Gujarat. Int J Agric Invent. 2026;11(1):79-83. https://doi.org/10.46492/ijai/2026.11.1.12

2. Neitsch SL, Arnold JG, Kiniry JR, Williams JR. Soil and water assessment tool theoretical documentation. Grassland (TX): Soil and Water Research Laboratory, Agricultural Research Service; 2005. https://doi.org/10.25175/jrd/2017/v36/i1/112705
3. Lotha TN, Ritse V, Nakro V, K K, I I, Rudithongru L, et al. Climate change impact and traditional adaptation practices in Northeast India: a review. Curr World Environ. 2024;19(2):558-75. https://doi.org/10.12944/cwe.19.2.5
4. Adhikari P, Mishra BK, Baral S. Sediment yield assessment in the Budhi Gandaki Basin Nepal using the SWAT model. Discov Geosci. 2026;4(1):1-25. https://doi.org/10.1007/s44288-026-00518-1
5. Gogoi B, Lahon D. Impact of climate change on biodiversity: an overview. Int J Biol Innov. 2019;1(2):60-5. https://doi.org/10.46505/ijbi.2019.1205
6. Khwairakpam E, Khosa R, Gosain A, Nema A, Mathur S, Yadav B. Modeling simulation of river discharge of Loktak Lake catchment in Northeast India. J Hydrol Eng. 2018;23(8):1-13. https://doi.org/10.1061/(asce)he.1943-5584.0001674
7. Chawanda CJ, van Griensven A, Nkwasa A, Orsini JPT, Jeong J, Choi SK, et al. CoSWAT Model v1: a high-resolution global SWAT+ hydrological model. Hydrol Earth Syst Sci. 2025;29(23):6901-16. https://doi.org/10.5194/hess-29-6901-2025
8. Singh TA, Meetei N, Meetei L. Seasonal variation of some physico-chemical characteristics of three major rivers in Imphal, Manipur: a comparative evaluation. Curr World Environ. 2013;8(1):93-102. https://doi.org/10.12944/cwe.8.1.10
9. Khwairakpam E, Khosa R, Gosain A, Nema A. Monitoring and modelling water quality of Loktak Lake catchment. SN Appl Sci. 2019;1(5):1-15. https://doi.org/10.1007/s42452-019-0517-1
10. Singh KJ. Urbanization growth in Manipur: its stress on the civic amenities on Loktak Lake. Int J All Res Educ Sci Methods. 2021;9(9):902-5.
11. Wandre S, Rank HD, Shinde V. Calibration and validation of the SWAT model for the Vartu River basin, Gujarat. Int J Agric Invent. 2025;10(2):29-33. https://doi.org/10.46492/ijai/2025.10.2.5
12. Ningthoujam V, Romeji N, Chanu LB. Sediment yield in an urbanized river basin: a case study of Nambul River, Manipur, India. Proc IAHR World Congr. 2022;2022:845-53. https://doi.org/10.3850/IAHR-39WC2521716X2022963
13. Opiyo SB. Modeling the impacts of land use and land cover changes on streamflow and sediment yield with the SWAT Model in Migori River Watershed, Lake Victoria Basin

Region, Kenya. Afr Geogr Rev. 2025 Jan 2;44(1):48-69. https://doi.org/10.1080/19376812.2024.2324279

14. Zhang Y, He Y, Song J. Effects of climate change and land use on runoff in the Huangfuchuan Basin, China. J Hydrol. 2023;626:130-195. https://doi.org/10.1016/j.jhydrol.2023.130-195
15. Dwarakish GS, Ganasri BP. Impact of land use change on hydrological systems: a review of current modeling approaches. Cogent Geosci. 2015;1(1):1115691. https://doi.org/10.1080/23312041.2015.1115691
16. Lin B, Chen X, Yao H, Chen Y, Liu M, Gao L, et al. Analyses of landuse change impacts on catchment runoff using different time indicators based on SWAT model. Ecol Indic. 2015;58:55-63. https://doi.org/10.1016/j.ecolind.2015.05.031
17. Tilahun AK. Land use land cover change and its implication on surface runoff: a case study of Baro River Basin in South Western Ethiopia. J Environ Earth Sci. 2015;5(8):53-8.
18. Nourani V, Abbasi H, Salehi AH, Aalami MT, Bejani M, Pourali H. Reconstructing hydrological drought using SWAT, deep learning models, and SSI. Water Resour Manage. 2026;40(5):1-28. https://doi.org/10.1007/s11269-025-04372-7
19. Martins LL, Martins WA, Ferreira MEC, Moraes JFL, Bolfe ÉL, Blain GC. SWAT model and drought indices: a systematic review of progress, challenges and opportunities. Water. 2026;18(1):1-28. https://doi.org/10.3390/w18010041
20. Bekele T, Kebede A, Moges A. An integrated assessment of soil erosion risk in the Bilate sub-basin of Southern Ethiopia using the SWAT model and multi-criteria decision analysis. Discov Sustain. 2026. https://doi.org/10.1007/s43621-026-03831-4
21. Rai R, Pardeshi SS, Pebam R. Geospatial assessment of soil erosion in the Kamlang River watershed using the RUSLE framework. Discov Geosci. 2026;4(1):275. https://doi.org/10.1007/s44288-026-00275-9
22. Abbaspour KC, Rouholahnejad E, Vaghefi S, Srinivasan R, Yang H, Kløve B. A continental-scale hydrology and water quality model for Europe: calibration and uncertainty of a high-resolution large-scale SWAT model. J Hydrol. 2015;524:733-52. https://doi.org/10.1016/j.jhydrol.2015.03.027
23. Malagò A, Pagliero L, Bouraoui F, Franchini M. Comparaison de jeux de paramètres calés de modèles SWAT pour les péninsules ibérique et Scandinave. Hydrol Sci J. 2015;60(5):949-67. French. https://doi.org/10.1080/02626667.2014.978332

24. Gassman PW, Reyes MR, Green CH, Arnold JG. The Soil and Water Assessment Tool: historical development, applications, and future research directions. Trans ASABE. 2007;50(4):1211-50. https://doi.org/10.13031/2013.23637
25. Faramarzi M, Abbaspour KC, Ashraf Vaghefi S, Farzaneh MR, Zehnder AJB, Srinivasan R, et al. Modeling impacts of climate change on freshwater availability in Africa. J Hydrol. 2013;480:85-101. https://doi.org/10.1016/j.jhydrol.2012.11.005
26. Guzha AC, Rufino MC, Okoth S, Jacobs S, Nóbrega RLB. Impacts of land use and land cover change on surface runoff, discharge and low flows: evidence from East Africa. J Hydrol Reg Stud. 2018;15:49-67. https://doi.org/10.1016/j.ejrh.2017.11.005
27. Setegn SG, Srinivasan R, Dargahi B. Hydrological modelling in the Lake Tana Basin, Ethiopia using SWAT model. Open Hydrol J. 2008;2(1):49-62. https://doi.org/10.2174/1874378100802010049
28. Betrie GD, Mohamed YA, Van Griensven A, Srinivasan R. Sediment management modelling in the Blue Nile Basin using SWAT model. Hydrol Earth Syst Sci. 2011;15(3):807-18. https://doi.org/10.5194/hess-15-807-2011
29. Githui F, Mutua F, Bauwens W. Estimating the impacts of land-cover change on runoff using the Soil and Water Assessment Tool (SWAT): case study of Nzoia catchment, Kenya. Hydrol Sci J. 2009;54(5):899-908. https://doi.org/10.1623/hysj.54.5.899
30. Easton ZM, Fuka DR, White ED, Collick AS, Biruk Ashagre B, McCartney M, et al. A multi basin SWAT model analysis of runoff and sedimentation in the Blue Nile, Ethiopia. Hydrol Earth Syst Sci. 2010;14(10):1827-41. https://doi.org/10.5194/hess-14-1827-2010
31. White ED, Easton ZM, Fuka DR, Collick AS, Adgo E, McCartney M, et al. Development and application of a physically based landscape water balance in the SWAT model. Hydrol Process. 2011;25(6):915-25. https://doi.org/10.1002/hyp.7876
32. Bera S, Maiti R. Assessment of water availability with SWAT model: a study on Ganga River. J Geol Soc India. 2021;97(7):781-8. https://doi.org/10.1007/s12594-021-1760-9
33. Jeffrey KM, Ngangbam R, E VR, D B, P LNR. Hydrologic modeling of umiam watershed using GIS and SWAT model. In: Proceedings of the National Symposium on Recent Advances in Remote Sensing & GIS with Special Emphasis on Mountain Ecosystems; 2016 Dec 7-9; Dehradun, India. Dehradun: Indian Society of Remote Sensing; 2016.
34. Choubey S, Kumari R, Chander S, Kumari P. Assessment of current and projected runoff in the Sabarmati river basin using CMIP6 climate projections and hydrological modelling. Discov Geosci. 2026;4(1):1-18. https://doi.org/10.1007/s44288-026-00452-2

35. Thampi SG, Raneesh KY, Surya TV. Influence of scale on SWAT model calibration for streamflow in a river basin in the humid tropics. Water Resour Manage. 2010;24(15):4567-78. https://doi.org/10.1007/s11269-010-9676-y
36. Sajikumar N, Remya RS. Impact of land cover and land use change on runoff characteristics. J Environ Manage. 2015;161:460-8. https://doi.org/10.1016/j.jenvman.2014.12.041
37. Iskender I, Sajikumar N. Evaluation of surface runoff estimation in ungauged watersheds using SWAT and GIUH. Procedia Technol. 2016;24:109-15. https://doi.org/10.1016/j.protcy.2016.05.016
38. Mishra A, Froebrich J, Gassman PW. Evaluation of the SWAT model for assessing sediment control structures in a small watershed in India. Trans ASABE. 2007;50(2):409-77.
39. Tripathi MP, Panda RK, Raghuwanshi NS. Development of effective management plan for critical subwatersheds using SWAT model. Hydrol Process. 2005;19(3):809-26. https://doi.org/10.1002/hyp.5618
40. Himanshu SK, Pandey A, Yadav B, Gupta A. Evaluation of best management practices for sediment and nutrient loss control using SWAT model. Soil Tillage Res. 2019;192:42-58. https://doi.org/10.1016/j.still.2019.04.016
41. Hallouz F, Meddi M, Mahé G, Alirahmani S, Keddar A. Modeling of discharge and sediment transport through the SWAT model in the basin of Harraza (Northwest of Algeria). Water Sci. 2018;32(1):79-88. https://doi.org/10.1016/j.wsj.2017.12.004
42. Yadav A, Singh RM. Crop yield estimation under future climatic conditions using SWAT model. Theor Appl Climatol. 2026;157(2):1-15. https://doi.org/10.1007/s00704-026-06059-4
43. Rostamian R, Jaleh A, Afyuni M, Mousavi SF, Heidarpour M, Jalalian A, et al. Application of a SWAT model for estimating runoff and sediment in two mountainous basins in central Iran. Hydrol Sci J. 2008;53(5):977-88. https://doi.org/10.1623/hysj.53.5.977
44. Spruill CA, Workman SR, Taraba JL. Simulation of daily and monthly stream discharge from small watersheds using the SWAT model. Trans ASAE. 2000;43(6):1431-9. https://doi.org/10.13031/2013.3041
45. Bosch DD, Sheridan JM, Batten HL, Arnold JG. Evaluation of the SWAT model on a coastal plain agricultural watershed. Trans ASABE. 2004;47(5):1493-506. https://doi.org/10.13031/2013.17621

46. Roy A, Kolday D, Paudel B, Yumnam A, Mridha N, Chakraborty D, et al. Recent trends and impacts of climate change in north-eastern region of India: a review. J Environ Biol. 2021;42(6):1415-24.
47. Roy SS, Ansari MA, Sharma SK, Sailo B, Basudha Devi C, Singh IM, et al. Climate resilient agriculture in Manipur: status and strategies for sustainable development. Curr Sci. 2018;115(7):1342-50. https://doi.org/10.18520/cs/v115/i7/1342-1350
48. Jamir T. Changes in land cover/land use over the northeast region of India. J Geogr Inst Jovan Cvijic SASA. 2015;65(3):309-22. https://doi.org/10.2298/ijgi1503309j
49. Kundu SS, Das AK, Chakraborty K, Sarma KK, Kundu SS, Kr A, et al. Shifting cultivation dynamics in Barak Basin of North East India: a geospatial approach. Int J Adv Earth Environ Sci. 2015;3(2):21-9. Available from: (https://www.researchgate.net/publication/291832672)
50. Al-Samawi I, Noman A, Khanbari K. The impacts of land-use change on the runoff characteristics using HEC-HMS model. 2019. Available from: (https://doi.org/10.1007/978-3-030-67028-3_10)
51. Al-Samawi I, Noman A, Khanbari K, Quriaa H, Al-Areeq N, Aklan M. The impacts of land-use change on the runoff characteristics using HEC-HMS model: a case study in Wadi Al-Mulaikhy Sub-Watershed in Sana'a Basin, Yemen. Adv Sci Technol Innov. 2021:121-30. https://doi.org/10.1007/978-3-030-67028-3_10
52. Guo Z, Feng C, Yang L, Liu Q. Bridging the gap: an interpretable coupled model (SWAT-ELM-SHAP) for blue-green water simulation in data-scarce basins. Agric Water Manag. 2024;306:109-57.
53. Arnold JG, Srinivasan R, Muttiah RS, Williams JR. Large area hydrologic modeling and assessment part I: model development. J Am Water Resour Assoc. 1998;34(1):73-89.
54. Shi P, Chen C, Srinivasan R, Zhang X, Cai T, Fang X, et al. Evaluating the SWAT model for hydrological modeling in the Xixian Watershed and a comparison with the XAJ model. Water Resour Manage. 2011;25(10):2595-612. https://doi.org/10.1007/s11269-011-9828-8
55. Pandi D, Kothandaraman S, Kuppusamy M. Simulation of water balance components using SWAT model at sub catchment level. Sustainability. 2023;15(2):1438. https://doi.org/10.3390/su15021438
56. Neitsch SL, Arnold JG, Kiniry JR, Williams JR. Soil & water assessment tool theoretical documentation version 2009. College Station (TX): Texas Water Resources Institute; 2011. Report No.: TR-406.

57. Arnold JG, Kiniry JR, Srinivasan R, Williams JR, Haney EB, Neitsch SL. SWAT: model use, calibration, and validation. Trans ASABE. 2012;55(4):1491-508.
58. Jayakrishnan R, Srinivasan R, Santhi C, Arnold JG. Advances in the application of the SWAT model for water resources management. Hydrol Process. 2005;19(3):749-62. https://doi.org/10.1002/hyp.5624
59. Brighenti TM, Čerkasova N, Stone TF, Gassman PW, Arnold JG, Kiniry JR, et al. Integrating new fruit and vegetable growth parameters in SWAT models for improved simulations. Front Plant Sci. 2026;17:1745017. https://doi.org/10.3389/fpls.2026.1745017
60. Zhang X, Jiang Y, Yan T, Xie K, Li P, Niu J, et al. Integrating GLASS LAI into the SWAT model for improved hydrological simulation in semi-arid regions. Agronomy. 2026;16(6):639. https://doi.org/10.3390/agronomy16060639
61. Ningthoujam V, Romeji N, Singh KS. Performance of SWAT hydrological model of partially-gauged Nambul River urbanized catchment in Manipur IHR, India. Asia-Pac J Sci Technol. 2023;28(5):APST-28-05-18. https://doi.org/10.14456/apst.2023.86
62. Zhang J, Li Q, Guo B, Gong H. The comparative study of multi-site uncertainty evaluation method based on SWAT model. Hydrol Process. 2015;29(13):2994-3009. https://doi.org/10.1002/hyp.10380
63. Gitau MW, Chaubey I. Regionalization of SWAT model parameters for use in ungauged watersheds. Water. 2010;2(4):849-71. https://doi.org/10.3390/w2040849
64. Thounaojam L, Oinam B. Evaluation of groundwater potential in Imphal-Nambul River sub-basin using GIS and AHP techniques. J Indian Soc Remote Sens. 2025;53(12):4081-93. https://doi.org/10.1007/s12524-025-02240-w
65. Bieger K, Hörmann G, Fohrer N. Detailed spatial analysis of SWAT-simulated surface runoff and sediment yield in a mountainous watershed in China. Hydrol Sci J. 2015;60(5):784-800.
66. Oo HT, Zin WW, Thin Kyi CC. Analysis of streamflow response to changing climate conditions using SWAT model. Civ Eng J. 2020;6(2):194-209. https://doi.org/10.28991/cej-2020-03091464
67. Ningthoujam V, Romeji N, Singh KS. Performance of SWAT hydrological model of partially-gauged Nambul River urbanized catchment in Manipur IHR, India. Asia-Pac J Sci Technol. 2023;28(5):APST-28-05-18. https://doi.org/10.14456/apst.2023.86
68. Zhang X, Srinivasan R, Van Liew M. Multi-site calibration of the SWAT model for hydrologic modeling. Trans ASABE. 2008;51(6):2039-49. https://doi.org/10.13031/2013.25407

69. Bosch DD, Sheridan JM, Batten HL, Arnold JG. Evaluation of the SWAT model on a coastal plain agricultural watershed. Trans ASABE. 2004;47(5):1493-506.
70. Bärlund I, Kirkkala T, Malve O, Kämäri J. Assessing SWAT model performance in the evaluation of management actions for the implementation of the Water Framework Directive in a Finnish catchment. Environ Model Softw. 2007;22(5):719-24. https://doi.org/10.1016/j.envsoft.2005.12.030
71. Mulungu DMM, Munishi SE. Simiyu River catchment parameterization using SWAT model. Phys Chem Earth. 2007;32(15-18):1032-9. https://doi.org/10.1016/j.pce.2007.07.053
72. Wu K, Xu YJ. Evaluation of the applicability of the SWAT model for coastal watersheds in southeastern Louisiana. J Am Water Resour Assoc. 2006;42(5):1247-60. https://doi.org/10.1111/j.1752-1688.2006.tb05610.x
73. Peterson JR, Hamlett JM. Hydrologic calibration of the SWAT model in a watershed containing fragipan soils. J Am Water Resour Assoc. 1998;34(3):531-44.
74. White KL, Chaubey I. Sensitivity analysis, calibration, and validations for a multisite and multivariable SWAT model. J Am Water Resour Assoc. 2005;41(5):1077-89. https://doi.org/10.1111/j.1752-1688.2005.tb03786.x
75. Zakari MD, Kamal MR, Ramli NM, Rehan BM, Bin Mohd MSF. Calibration and validation of the SWAT model for Upper Bernam River Basin in Malaysia. Nauk Visn Nats Hirn Univ. 2025;(6):168-78. https://doi.org/10.33271/nvngu/2025-6/168
76. Congalton RG. A review of assessing the accuracy of classifications of remotely sensed data. Remote Sens Environ. 1991;37(1):35-46.
77. Foody GM. Status of land cover classification accuracy assessment. Remote Sens Environ. 2002;80(1):185-201.
78. Reimeingam M. Shifting cultivation in Manipur: land, labour and environment. J Rural Dev. 2017;36(1):97-119. https://doi.org/10.25175/jrd/2017/v36/i1/112705
79. Ministry of Environment, Forest and Climate Change. India State of Forest Report 2021. Dehradun: Forest Survey of India; 2021.
80. De UK, Devi LH. Inequality dynamics in urban Manipur, India: a decomposition analysis. Soc Indic Res. 2023;167(1):67-89. https://doi.org/10.1007/s11205-023-03096-8
81. Moriasi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel RD, Veith TL. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans ASABE. 2007;50(3):885-900.

82. Wang S, McVicar TR, Zhang Z, Brunner T, Strauss P. Globally partitioning the simultaneous impacts of climate-induced and human-induced changes on catchment streamflow: a review and meta-analysis. J Hydrol. 2020;590:125387. https://doi.org/10.1016/j.jhydrol.2020.125387
83. Siriwardena L, Finlayson BL, McMahon TA. The impact of land use change on catchment hydrology in large catchments: the Comet River, Central Queensland, Australia. J Hydrol. 2006;326(1):199-214. https://doi.org/10.1016/j.jhydrol.2005.10.030