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Modeling Hydrological Impacts of Land-Use Change in the Sam Ngao Watershed Using SWAT and CA-Markov

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ABSTRACT

This study investigates the hydrological consequences of Land Use and Land Cover (LULC) transformations within the Sam Ngao Watershed (SNgW) from 2000 to 2020. Utilizing the Soil and Water Assessment Tool (SWAT), the research simulates watershed hydrological responses to observed LULC dynamics. To forecast future hydrological conditions, LULC scenarios for 2040 and 2060 were generated using a hybrid Cellular Automata-Markov Chain (CA-Markov) modeling approach. A hybrid classification methodology enhanced the accuracy of LULC mapping from Landsat imagery, integrating multiple classification techniques. Results reveal that LULC alterations between 2000 and 2020 significantly influenced the watershed’s hydrological regime, including declines in dry season flow (7.36%), groundwater discharge (25.43%), and evapotranspiration rates (7.63%), and increases in average annual streamflow (9.85%), wet season streamflow (12.85%), and surface runoff (33.21%). These shifts are primarily attributed to agricultural expansion and deforestation. Projected LULC changes for 2040–2060 indicate a potential reversal in trends, with increases in dry season flow, groundwater recharge, and evapotranspiration, accompanied by decreases in annual and wet season streamflow as well as surface runoff. Hydrological impacts were notably heterogeneous across sub-watersheds, reflecting the spatially uneven distribution of LULC changes. These findings offer valuable insights for decision-makers, water resource managers, and local stakeholders toward creating adaptive strategies for sustainable water resource management in the SNgW and analogous catchments. The study supports international efforts aligned with Sustainable Development Goal 6 (SDG 6) to secure universal access to clean water and sanitation through sustainable management, and with SDG 11 to create sustainable cities and communities through resilient infrastructure, inclusive urban planning, and climate-adaptive water management systems. The outcomes also provide a robust scientific foundation for researchers and policy developers engaged in hydrology, watershed management, and national land use planning frameworks.

Keywords: land use and land cover, hydrological modeling, SWAT, CA-Markov, watershed hydrology

INTRODUCTION

Globally, rapid transformations in Land Use and Land Cover (LULC) are predominantly driven by urbanization, population growth, and intensified agricultural practices. These transformations exert profound influences on water quality, ecosystem functionality, and natural hydrological flows, thereby altering watershed hydrological processes and water resource availability (Aragaw et al., 2021; Aragaw et al., 2022; Gashaw et al., 2018; Gebremicael et al., 2018; Koren & Chaves, 2025; Mehra & Swain, 2024). A comprehensive understanding of hydrological responses to both historical and projected LULC changes is essential to inform optimal water resource management, land use planning, and sustainable development strategies. Anthropogenic activities have historically reshaped natural landscapes by modifying surface characteristics, vegetation cover, and soil properties, which subsequently affect precipitation interception, evapotranspiration, infiltration, runoff generation, and groundwater recharge (Bawa et al., 2025; Gashaw et al., 2018;). As land use patterns continue to evolve under the pressures of global population expansion, urban growth, and intensified agriculture, the ability to predict and evaluate future land use scenarios becomes increasingly critical (Bawa et al., 2025; Faksomboon, 2022; Hansasooksin et al., 2024; Likitswat & Sahavacharin, 2022; Wang et al., 2020; Yang et al.; 2019). Such changes emphasize the necessity of integrating hydrological considerations within land use planning frameworks to mitigate adverse environmental impacts and promote sustainable watershed management. Predictive assessments of hydrological responses to future LULC alterations are vital for adaptive water resource management, strategic land use planning, and climate change resilience, thus supporting evidence-based policy formulation and sustainable practice implementation.

In Thailand's highland regions, significant challenges associated with LULC changes and land degradation have emerged. Accelerated population growth has led to the conversion of natural vegetation into agricultural land. The Sam Ngao Watershed (SNgW) (Figure 1), a sub-basin of the Ping watershed, exemplifies this trend, experiencing notable land degradation marked by the replacement of natural vegetation with agricultural and urban landscapes. Currently, the watershed faces escalating threats including forest degradation, expansion of agricultural land, disruptions to hydrological systems, agricultural burning, and unplanned settlements resulting from rapid immigration (Chakir et al., 2025; F aksomboon, 2023; Hu et al., 2025; Numsuk, 2025; Tontisirin & Anantsuksomsri, 2021). While previous investigations have largely focused on documenting historical land use changes, there is an increasing demand for projections of future LULC scenarios and their consequent impacts on hydrological and environmental processes (Abuhay et al., 2023; Aragaw et al., 2021; Faksomboon et al., 2024; Hu et al., 2025; Musie et al., 2020;; Pongratz et al., 2021). However, current research is constrained by a lack of long-term projections that capture progressive LULC dynamics, a limited understanding of hydrological impacts at the sub-watershed resolution, and scarce applications that integrate CA-Markov modeling with SWAT for comprehensive scenario-based assessments in this geographical context. CA-Markov, with its proven ability to simulate spatial temporal land use transitions, and SWAT, a process-based hydrological model capable of quantifying detailed water balance components, offer a synergistic framework for linking LULC dynamics with hydrological responses. Despite their complementary strengths, their combined application remains underutilized in Thailand's mountainous sub-watersheds, particularly for long-term, scenario-based analyses. Many extant studies inadequately address the prediction and evaluation of future land use dynamics. Given the ongoing evolution of land use, elucidating the hydrological impacts of anticipated changes is critical for informed water management and sustainable land use planning. Although multiple studies have assessed hydrological responses to LULC variations across Thailand, their focus has primarily been on major watersheds. In contrast, more pronounced hydrological impacts frequently occur at the sub-watershed scale, driven by localized spatial heterogeneity in land use patterns (Aragaw et al., 2021; Marhaento et al., 2017; Silabi et al., 2025), while compensatory hydrological effects often moderate impacts at the larger watershed scale (Bagwan & Gavali, 2025; Irvine et al, 2023; Shawul et al., 2019). Consequently, developing effective mitigation and adaptation strategies necessitates a detailed understanding of LULC impacts on hydrology at the sub-watershed level (Chen et al., 2025; Marhaento et al., 2017; Saputra et al., 2025). Addressing these research gaps is paramount for sustainable water resource management, land use planning, and climate adaptation in the SNgW region. By filling these knowledge voids, this study aims to advance the scientific understanding of land-water interactions and provide robust data to support evidence-based decision making. Specifically, this research seeks to: (1) analyze historical LULC changes by identifying major land use transitions and quantifying cover dynamics over a defined period; (2) assess hydrological responses to historical LULC changes by examining key components such as surface runoff, evapotranspiration, lateral flow, water yield, groundwater flow, and percolation at both watershed and sub-watershed scales; and (3) project future LULC changes and evaluate their potential hydrological impacts using Cellular Automata-Markov Chain (CA-Markov) modeling, Geographic Information Systems (GIS), Remote Sensing (RS) techniques, and the Soil and Water Assessment Tool (SWAT).

LITERATURE REVIEW

Study Area and Data Description

The SNgW is strategically situated in northeastern Thailand, spanning longitudes 98^{0}26'28.29"E to 99^{0}04'25.35"E and latitudes 17^{0}05'50.01"N to 18^{0}03'48.99"N, for a total area of 2,390.65 km^2. This watershed extends across several provinces, including Chiang Mai, Lampang, Lamphun, and Tak, and functions as a critical sub-watershed within the larger Ping Watershed system. The soil composition within the SNgW is predominantly soil-20, accounting for 96.74% of the area, followed by soil-3 (2.44%), soil-18 (0.74%), and soil-14 (0.08%). The LULC in the watershed are classified into nine categories: deciduous forest, evergreen forest, field crops, miscellaneous, orchards, paddy fields, urban and built-up areas, reservoirs, and water bodies. Among these, deciduous forest constitutes the largest land cover type, occupying 1,642.06 km^2 or 68.51% of the total watershed area. This heterogeneous distribution of LULC significantly influences the hydrological processes and ecological integrity of the watershed, thereby impacting water resource management and sustainable land use planning. Evergreen forests cover 515.28 km^2 (21.55%), reservoirs account for 125.47 km^2 (5.25%), and water bodies cover 61.96 km^2 (2.59%) of the watershed area. The topography of the SNgW is characterized by high elevations surrounded by mountainous terrain, with elevation values ranging from 0 to 2,064 meters above mean sea level (MSL), as represented by the Digital Elevation Model (DEM) (Figure 2). This diverse LULC pattern plays a vital role in shaping the watershed's hydrological dynamics and maintaining its ecological health, which are critical for effective water resource management and sustainable land use planning.

Model Input Data

This study utilized various essential datasets, including LULC, DEM, soil characteristics, climate variables (temperature and precipitation), and streamflow data, to analyze and simulate hydrological responses to LULC changes within the watershed.

LULC

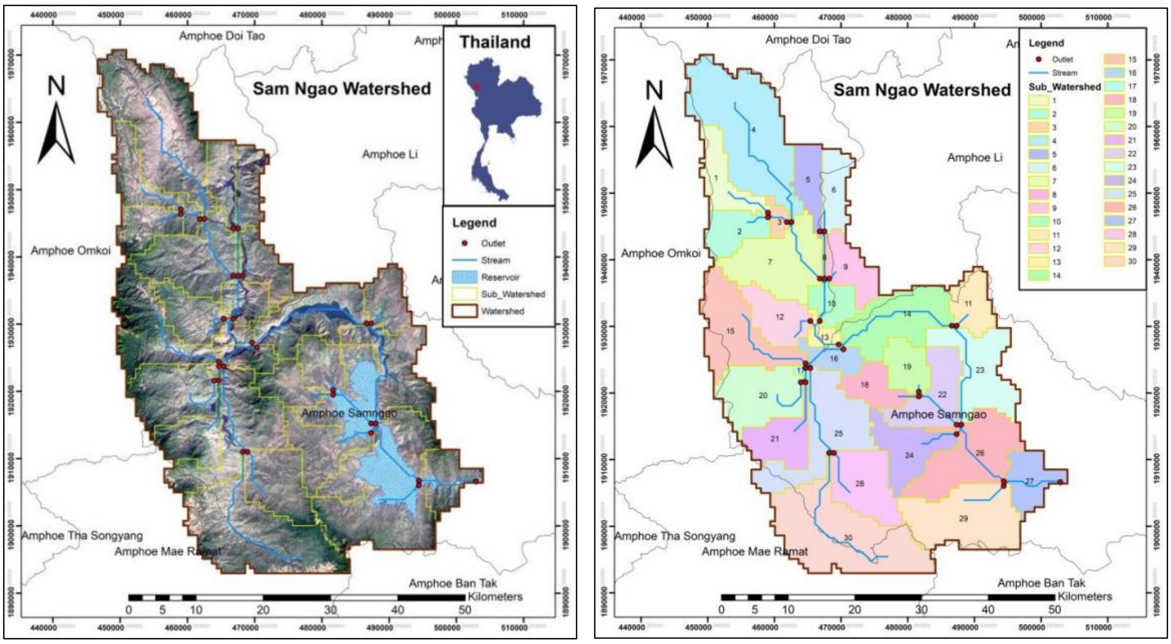
LULC datasets were acquired from the USGS Earth Explorer platform (http://earthexplorer.usgs.gov) using Landsat imagery captured during the dry season months (December to February) to minimize the influence of cloud cover and seasonal variability on classification accuracy. The datasets correspond to the years 2000, 2010, and 2020 and were derived from Landsat-7 and Landsat-8 satellites. These specific years were selected because they represent periods with high-quality imagery availability and provide consistent decadal intervals, which are essential for detecting systematic LULC trends and ensuring temporal coherence in long-term modeling applications. All datasets were processed and digitized with ArcGIS software to produce detailed LULC maps for the study area.

DEM and Soil

A 30 m × 30 m resolution DEM was obtained from the USGS Earth Explorer, specifically from the Shuttle Radar Topographic Mission (SRTM). This DEM was employed within the ArcSWAT environment for watershed delineation, flow accumulation analysis, extraction of sub-watershed parameters such as elevation and slope, and definition of the stream network. Soil maps and associated properties were provided by the Land Development Department of Thailand.

Figure 1

Location Map of the SNgW (a), Sub-Watershed, Stream, Reservoir, and Outlet (b)

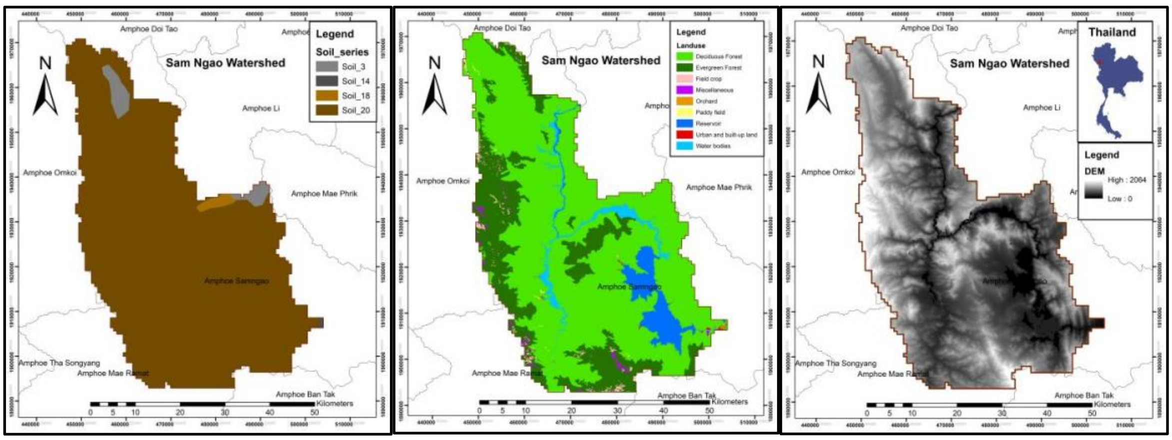


(a) (b)

Note. (a) Adapted from *Location Map of the SNgW*, by Google Earth Pro, 2024. Copyright 2024 by Google LLC.

Figure 2

The SNgW of Soils Map (a), LULC Map (b), and Topography Map (c)

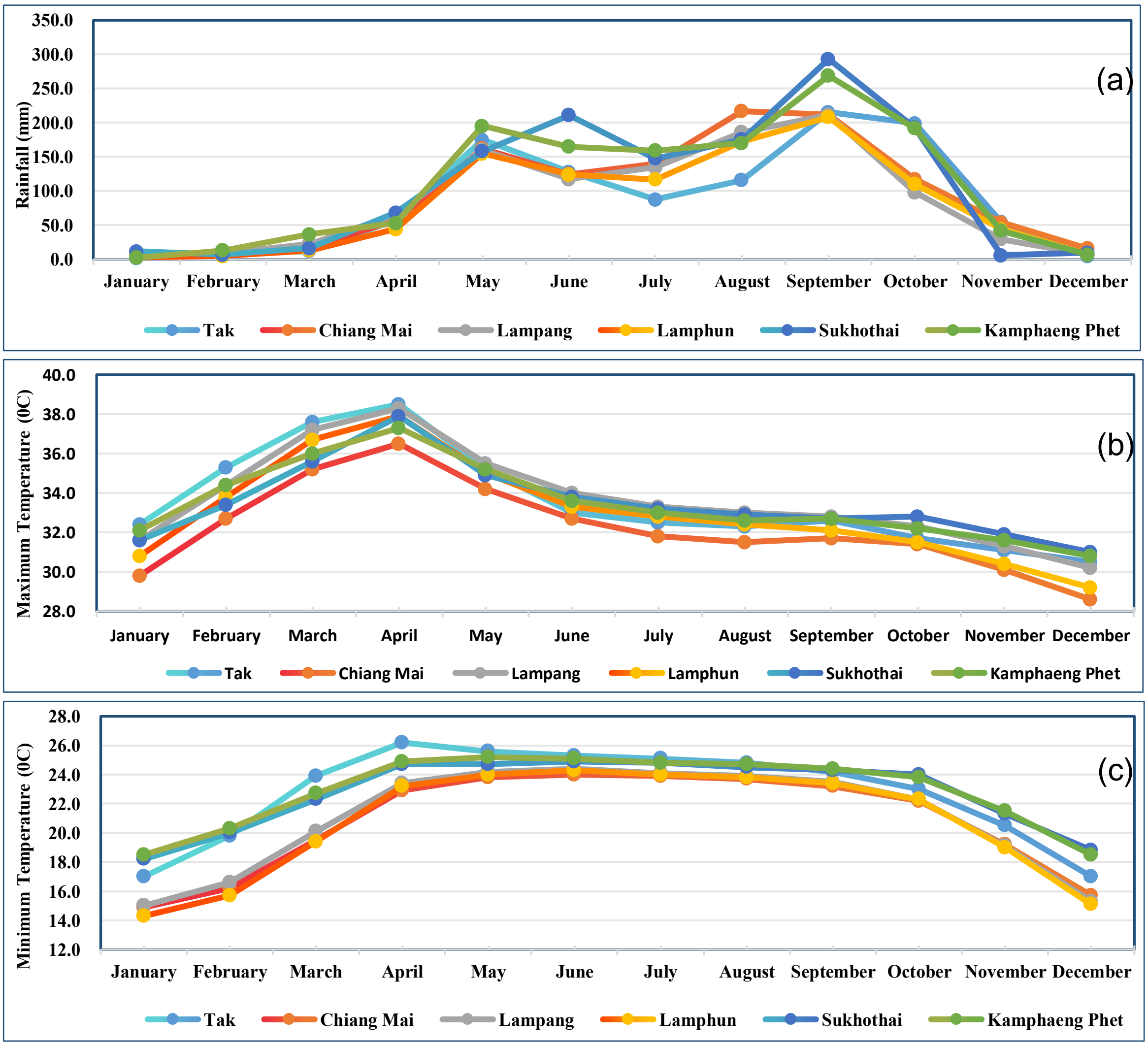


Hydro-Meteorological Data

Calibration and validation of the SWAT model required accurate discharge data, which were obtained from the Hydro-Informatics Institute (HII) of Thailand. Daily streamflow records from 2000 to 2020 at the Sam Ngao station (P.12C) within the Tak Province, Lower Northern Region Irrigation Hydrology Center, were compiled and aggregated into monthly values according to SWAT model requirements. Additionally, daily meteorological inputs, including precipitation, maximum and minimum temperature, solar radiation, wind speed, and relative humidity, were collected from six meteorological stations in and around the watershed, provided by the Thai Meteorological Department for the period of January 1, 2000, to December 31, 2020 (Figure 3). Due to incomplete records for variables such as wind speed and solar radiation at some stations, a weather generator simulation technique was applied to generate synthetic data. This statistical method replicates the temporal patterns and statistical characteristics of observed weather variables using historical data, enabling the production of realistic synthetic weather inputs necessary for applications such as agricultural planning, climate change impact assessment, and hydrological modeling. Within the SWAT model, the integrated weather generator, specifically the WGEN model, facilitates the simulation of missing meteorological data to ensure comprehensive input datasets (Asadi et al., 2025; Tan & Yang, 2020).

Figure 3

Average Monthly Rainfall (a), Maximum Temperature (b), and Minimum Temperature (c) at Each Station



METHODOLOGY

The methodology adopted in this study consisted of four main steps: a) classification of historical LULC, b) prediction of future LULC changes, c) setup of the hydrological model (SWAT model), including calibration and validation for the SNgW, and d) assessment of the impacts of LULC changes on water components at both watershed and sub-watershed scales. Figure 4 illustrates the overall research workflow.

LULC Classification and Prediction

Landsat imagery, specifically Landsat-8 OLI_TIRS data from 2020 and Landsat-7 TM data from 2000 and 2010, were utilized for LULC classification. To ensure the images were suitable for classification, they underwent a series of pre-processing procedures designed to enhance image quality and suitability (Aragaw et al., 2021; Hu et al., 2025). The entire study area was covered by mosaicking the satellite images. Radiometric enhancement techniques were applied to improve classification accuracy. A hybrid classification approach (Aragaw et al., 2021; Gashaw et al., 2017, Gashaw et al., 2018; Javed et al., 2024) was employed, combining unsupervised and supervised classification methods. The unsupervised classification was conducted using ISODATA clustering, while the supervised classification employed the Maximum Likelihood Classification (MLC) method. Mapping and classification of the SNgW were performed using ArcGIS 10.8 and ERDAS Imagine software. The classification accuracy assessment showed an overall accuracy of 89.5% and a Kappa coefficient of 0.87, indicating a high level of agreement and reliability of the LULC maps for subsequent hydrological and land use modeling.

Future LULC maps for the SNgW were predicted using the IDRISI 18.31 CA-Markov model. This model utilized historical LULC images, transition probability matrices, and suitability maps as inputs (Belhaj et al., 2025; Hansasooksin et al., 2024; Naeem et al., 2025; Wang et al., 2012). The transition probability matrix indicates the likelihood of transitions between LULC classes, while the transition area matrix specifies the expected number of pixels undergoing change over time. Suitability maps were generated based on factors such as proximity to urban centers, distance from streams and roads, and terrain variables derived from the DEM including elevation and slope (Ghosh et al., 2017; Xiang et al., 2025).

A simulated 2020 LULC map was generated using historical maps (2000-2010) and validated against the actual 2020 map. After successful validation, the 2020 map served as the baseline for predicting LULC maps for 2040 and 2060 using transition probability matrices. Equations (1) and (2) were applied to calculate the areal extent of LULC types and their rates of change, respectively.

Percentage area of LULC =

$$\frac{Area\ of\ each\ LULC\ class}{Total\ area\ of\ ABC\ watershed}\ x\ 100 \qquad (1)$$

$$\text{Rate of change (km}^2\text{/year)} = \frac{A-B}{Z} \qquad (2)$$

Where *A* is the area of LULC (km^2) at time - 2*, B* is the area of LULC (km^2) at time - 1;
Z is the time interval between *A* and *B* years.

SWAT Model

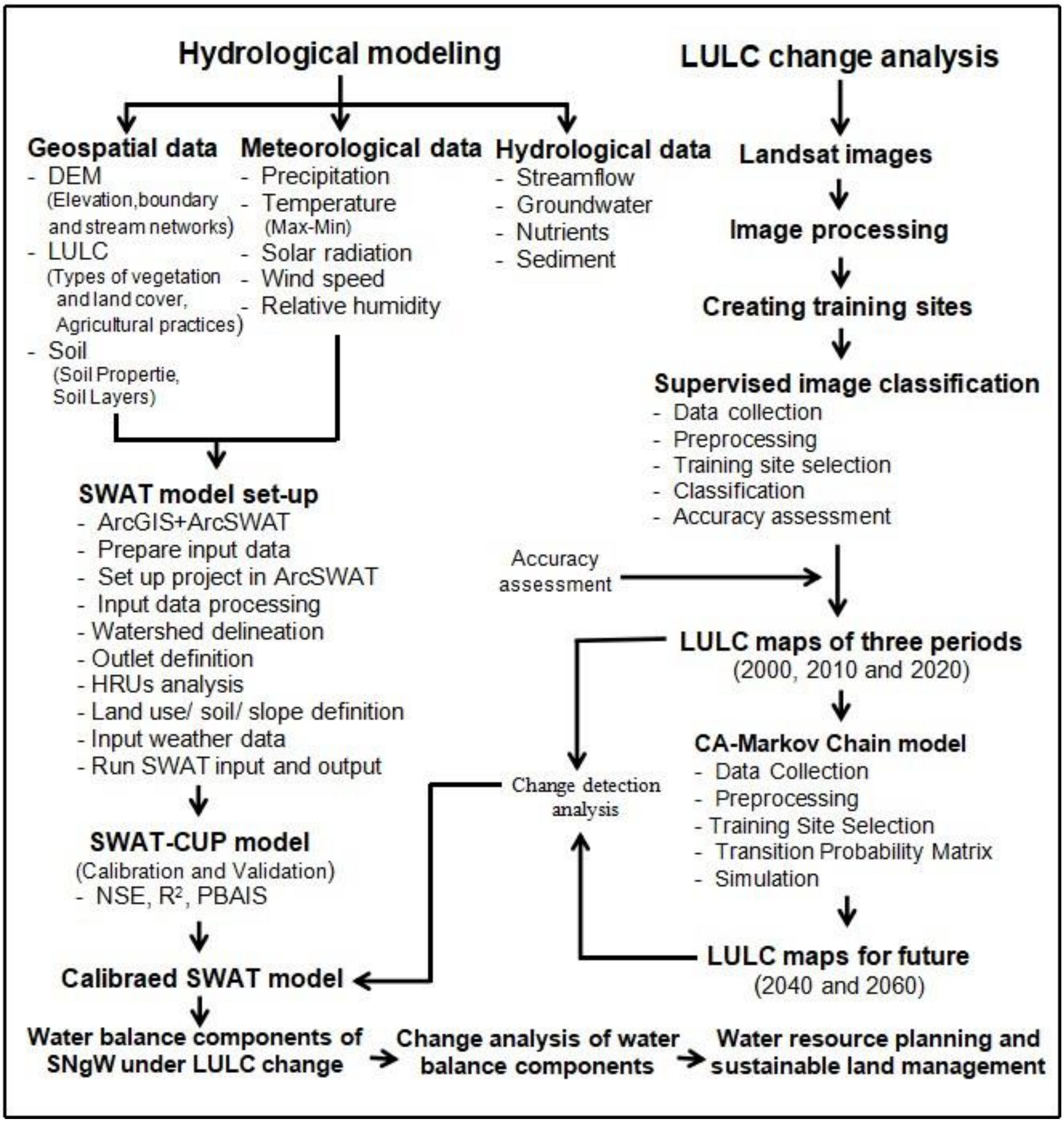
The SWAT is a semi-distributed hydrological model developed by the United States Department of Agriculture's Agricultural Research Service (USDA-ARS). This physically-based model is designed to simulate and predict the impacts of land management practices on water quantity, sediment transport, and agricultural chemical yields in large and complex watersheds with diverse spatial and temporal characteristics. SWAT divides the watershed into multiple sub-watersheds, with each further subdivided into Hydrologic Response Units (HRUs). HRUs represent unique combinations of slope, soil type, and land cover within each sub-watershed. In this study, the watershed was delineated into 186 HRUs, allowing detailed simulation of spatial heterogeneity. The model simulates hydrological processes and outputs at the HRU or sub-watershed level. Based on the water balance equation (Equation 3), SWAT performs daily simulations of watershed hydrology using inputs such as climate data, topography, soil properties, vegetation, and land management practices.

SWAT Model Setup / Calibration and Validation of Model

Model outputs are analyzed comprehensively to understand the watershed's hydrological behavior and support decision-making regarding effective management strategies. SWAT interpolates meteorological data through the Nearest Neighbor and centroid methods, assigning rainfall values from the closest rain gauge to each sub-watershed centroid. Evapotranspiration is simulated using the Penman-Monteith method; lateral flow is modeled with the kinematic storage method, and surface runoff is estimated using the modified Soil Conservation Service Curve Number (SCS-CN) method. Calibration involves adjusting model parameters based on literature, expert knowledge, and default settings to match observed data, while validation tests the model's predictive capability against independent datasets without further parameter changes. The calibration and validation processes utilize SWAT-CUP software employing the SUFI-2 algorithm. Sensitivity analysis is conducted using t-statistics and p-values to quantify the influence and significance of each model parameter.

Figure 4

Methodological Framework of the Study



$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (3)$$

Where: SW_t is the soil water content at time t, SW_0 is the initial soil water content, R_{day} is the daily rainfall, Q_{surf} is the surface runoff, E_a is the evapotranspiration, W_{seep} is the water that seeps into the soil, and Q_{gw} is the groundwater flow.

Model Performance Evaluation

Model performance was evaluated using the coefficient of determination (R^2, Equation 4), Nash-Sutcliffe efficiency (NSE, Equation 5), and percent bias (PBIAS, Equation 6), which are standard metrics for quantifying a model's ability to reproduce observed data.

$$R^2 = \left\{\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right) \times \left(Y_i^{sim} - X^{mean}\right)}{\sqrt{\left[\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2\right]} \times \sqrt{\sum_{i=1}^{n}\left(Y_i^{sim} - X^{mean}\right)^2}}\right\}^2 \quad (4)$$

$$NSE = \left\{1 - \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i-1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2}\right\} \quad (5)$$

$$PBAIS = \left\{\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right) * 100}{\sum_{i=1}^{n}\left(Y_i^{obs}\right)}\right\} \quad (6)$$

Where, n is the total number of observations, Y_i^{obs} is the observed value (m^3/s), Y_i^{sim} is the simulated value (m^3/s), Y^{mean} is the mean of the observed value (m^3/s), and X^{mean} is the mean of the simulate value (m^3/s). R^2 ranges from zero to one, with zero indicating poorness and one goodness of the model. *NSE* value ranges from negative infinity to 1, when the *NSE* value is greater than 0.5, the simulated value is a better predictor than the mean measured value and is generally considered acceptable performance. The optimal *PBIAS* value is zero, while positive and negative values indicate model underestimation and overestimation biases, respectively (Arnold et al., 2012).

Model Execution and Simulation Analysis

The calibrated and validated hydrological model was employed to simulate watershed hydrological responses under various LULC scenarios. Five independent simulations were performed using LULC maps corresponding to the years 2000, 2010, 2020, 2040, and 2060, while all other input parameters were held constant. This approach enabled a rigorous assessment of the temporal effects of LULC changes on the hydrological dynamics of the watershed. By maintaining constant input parameters aside from LULC, the analysis isolated and clearly identified the influence of land cover changes on key hydrological components, including surface runoff, evapotranspiration, lateral flow, percolation, water yield, and groundwater flow.

RESULTS

LULC Change Detection

Figure 5 displays the LULC maps for the years 2000, 2010, and 2020, with land cover categorized into nine classes: deciduous forest, evergreen forest, field crops, miscellaneous land, orchards, paddy fields, urban and built-up areas, reservoirs, and water bodies. Table 1 and Figure 6 present the spatial extent and rates of LULC changes from 2000 to 2060. Significant transformations occurred between 2000 and 2020, with trends expected to persist through 2040 and 2060. Between 2000 and 2010, the proportions of field crop and paddy field areas increased from 0.66% and 0.27% to 0.76% and 0.41%, respectively. In contrast, the coverage of deciduous forest, evergreen forest, miscellaneous land, and orchards decreased from 68.51%, 21.55%, 0.48%, and 0.41% to 68.38%, 21.45%, 0.47%, and 0.38%, respectively. From 2010 to 2020, urban and built-up areas expanded from 0.29% to 0.32%. These land use changes were primarily driven by population growth, which increased the demand for fuelwood and new agricultural land, leading to declines in other LULC categories.

Figure 5

LULC Maps for the Years 2000 (a), 2010 (b), 2020 (c), 2040 (d), and 2060 (e)

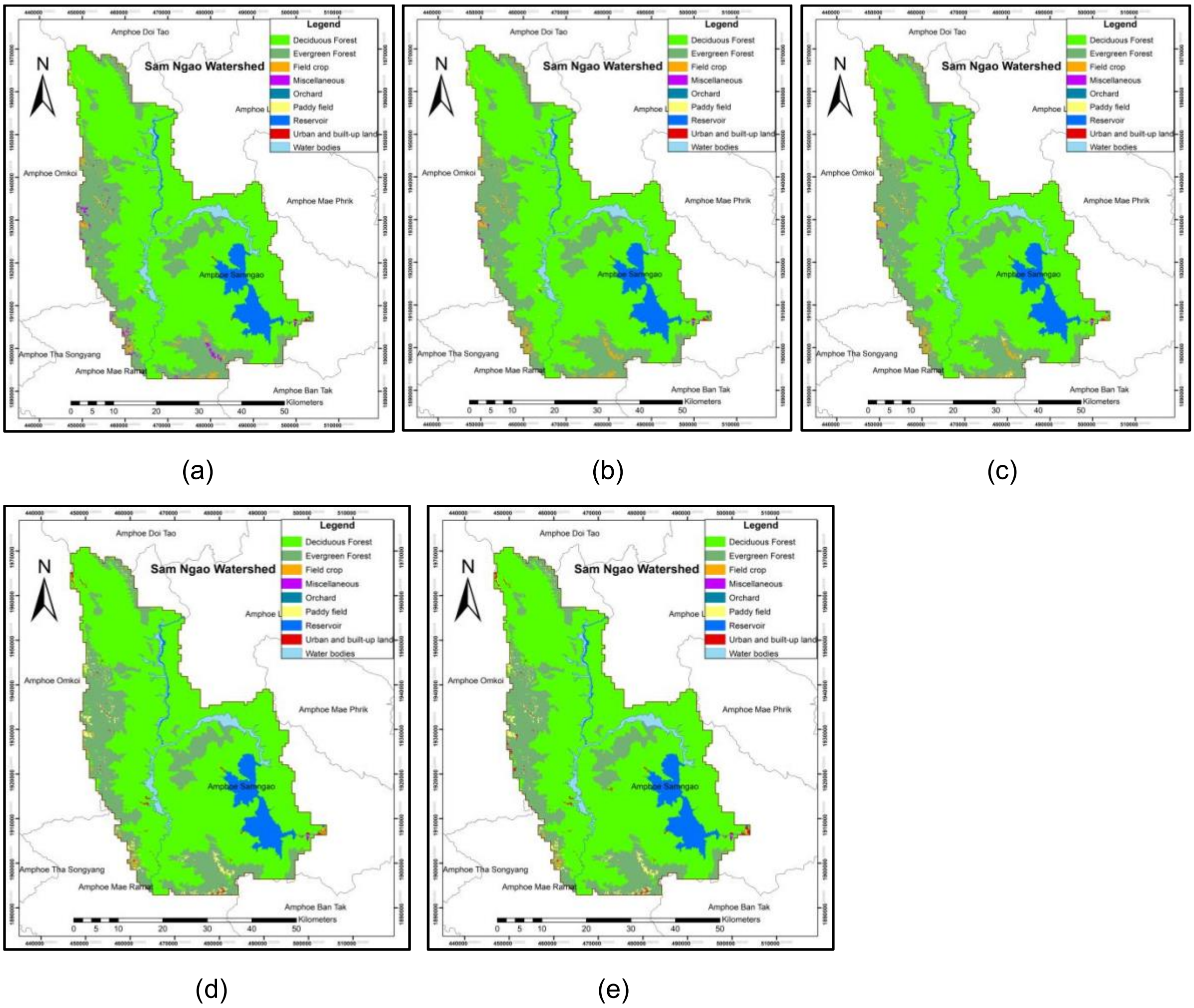


Table 1

The SNgW Area Extents for Historical and Future LULC Classes

Order	LULC Classes	Historical LULC Area (%)			Predicted LULC Area (%)	
		2000	2010	2020	2040	2060
1	Deciduous forest	68.51	68.38	68.20	67.95	67.79
2	Evergreen forest	21.55	21.45	21.34	21.23	21.13
3	Field crop	0.66	0.76	0.91	1.09	1.22
4	Miscellaneous	0.48	0.47	0.46	0.45	0.44
5	Orchard	0.41	0.38	0.35	0.32	0.28
6	Paddy field	0.27	0.41	0.55	0.73	0.86
7	Reservoir	5.25	5.25	5.25	5.25	5.25
8	Urban and built-up land	0.29	0.32	0.35	0.39	0.43
9	Water body	2.59	2.59	2.59	2.59	2.59
Total		100.00	100.00	100.00	100.00	100.00

The CA-Markov model was employed to forecast future LULC changes in the SNgW, projecting a continued expansion of agricultural lands alongside a decline in both deciduous and evergreen forest cover if current trends persist. Historically, the most pronounced decrease in deciduous and evergreen forests occurred between 2010 and 2020. In contrast, this period also experienced the highest rates of increase in field crops, paddy fields, and urban and built-up areas. Projections suggest that between 2020 and 2040, the watershed will undergo the most significant forest loss, coupled with substantial growth in agricultural lands and urban development.

These results emphasize the urgent need for proactive measures to mitigate potential hydrological consequences and promote sustainable water resource management in the SNgW. Historical and projected LULC dynamics highlight the critical importance of adopting effective land management strategies. Such interventions may include reforestation efforts, promotion of sustainable agricultural practices, and urban planning focused on incorporating green infrastructure. By addressing these challenges in advance, policymakers and resource managers can better preserve the watershed's ecological integrity and hydrological stability, thereby supporting broader environmental sustainability objectives.

SWAT Model Calibration and Validation

Sensitivity analysis revealed sixteen key parameters that exerted a significant influence on the hydrological processes within the SNgW watershed (Table 2). The initial parameter ranges for calibration were established based on authoritative guidelines from the SWAT input/output documentation (Arnold et al., 2012) and validated by reference to the SWAT-CUP database. These parameters were systematically adjusted during calibration to optimize model performance in simulating streamflow and related hydrological components. The calibration and validation procedures ensured that the SWAT model could accurately replicate observed hydrological behavior across multiple temporal scales, thereby increasing confidence in its predictive capabilities for watershed management applications.

Figure 6

The LULC Change Rate of SNgW Between 2000 and 2060

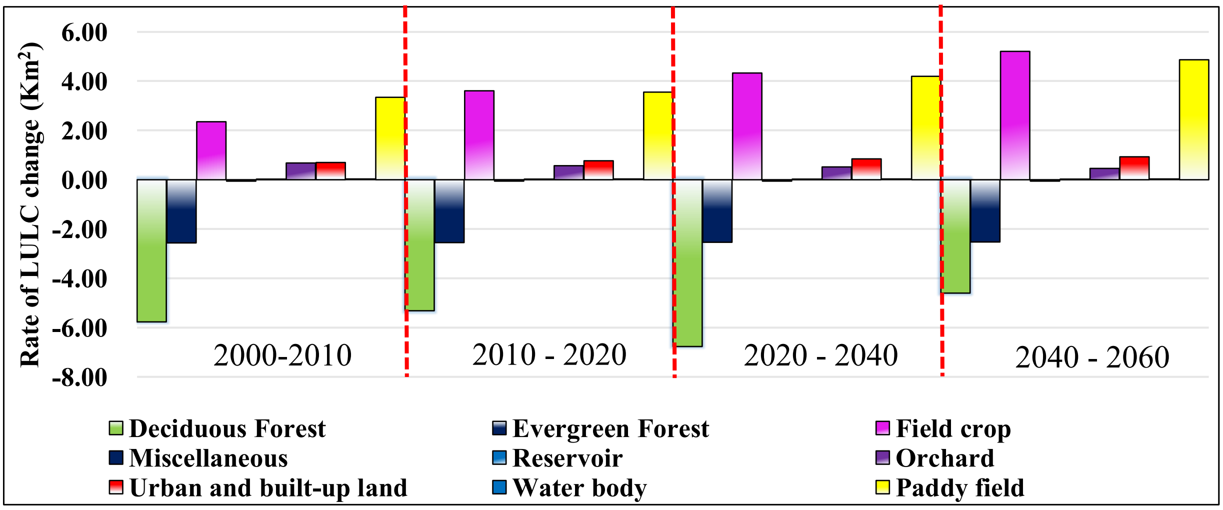


Table 2

Optimal Values, Sensitivity Rankings, and Parameter Ranges. The t-Statistic and p-Value Were Used to Establish Ranks

Order	Parameter	Input File	Range	t-Value	p-Value	Optimized Value	Rank
1	v__RCHRG_DP	.gw	0-1	30.45	> 0.01	0.523	1
2	r__CN2	.mgt	±0.25	22.74	> 0.01	0.215	2
3	v__CH_K2	.rte	0.01-150	18.52	> 0.01	89.517	3
4	v__GW_REVAP	.gw	0.02-0.2	-14.68	> 0.01	0.128	4
5	v__ALPHA_BF	.gw	0-1	-7.63	0.012	0.072	5
6	v__ESCO	.hru	0-1	-5.13	0.019	0.174	6
7	v__GWQMN	.gw	±1000	-3.58	0.041	714.246	7
8	r__SOL_AWC	.sol	±0.25	-2.63	0.074	-0.137	8
9	v__SPCON	.bsn	0.001-0.01	1.77	0.132	0.004	9
10	v__CANMX	.hru	0-10	1.28	0.187	2.891	10
11	v__GW_REVAP	.gw	0.02-0.2	-1.01	0.249	0.027	11
12	r__SOL_K	.sol	±0.25	-0.553	0.513	0.284	12
13	r__HRU_SLP	.hru	-0.2-0.2	-0.235	0.834	-0.163	13
14	v__REVAPMN	.gw	±100	0.763	0.497	64.571	14
15	r__SLSUBBSN	.hru	0-0.2	-0.479	0.633	0.063	15
16	v__GW_DELAY	.gw	0-500	-0.92	0.381	24.187	16

Note. v_ = Existing parameter value is multiplied by (1 + given value)

r_ = Existing parameter value is to be replaced by a given value

The SWAT model demonstrated high proficiency in replicating the hydrological behavior of the SNgW, as evidenced by the monthly hydrographs generated during calibration and validation periods, which closely correspond to the observed streamflow and areal precipitation data (Figure 7). Quantitative performance indicators further validated the model's capability to reliably simulate streamflow dynamics across both temporal phases.

Table 3 and Figure 8 present a comprehensive assessment of the SWAT model's accuracy in replicating hydrological processes within the study watershed. The evaluation metrics employed provide a rigorous comparison between the simulated outputs and observed datasets for both calibration and validation periods, thereby demonstrating the model's robustness and reliability in capturing watershed-scale hydrological dynamics.

Figure 7

Monthly Streamflow Simulations and Observations are Calibrated and Validated

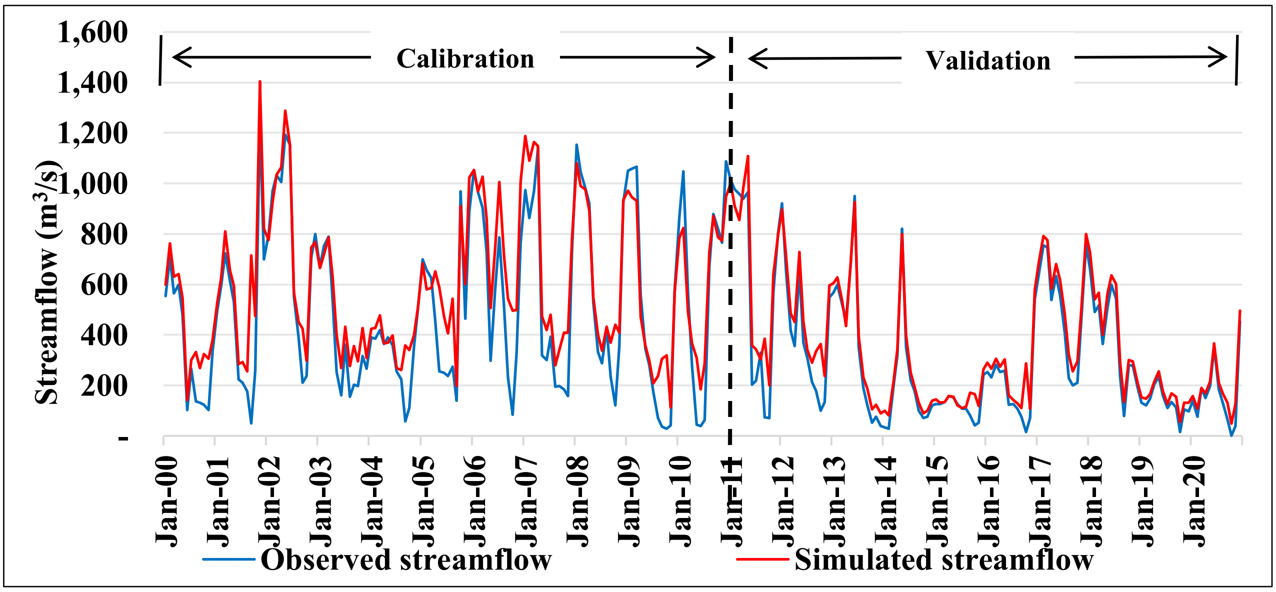


Table 3

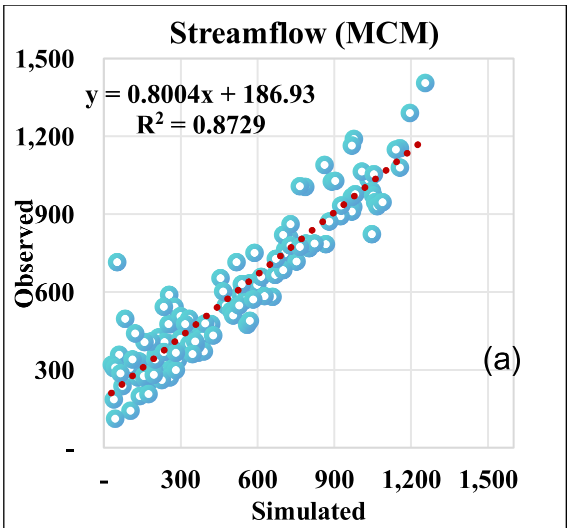
Performance Indicators for the Validation and Calibration of the SWAT Model

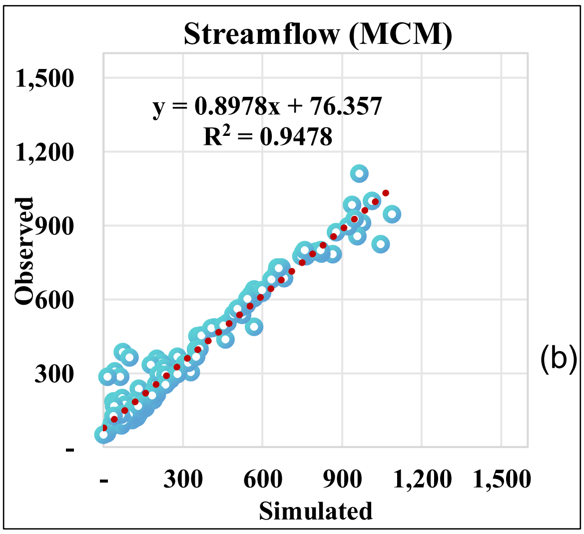
Order	Period	R^2	NSE	PBIAS
1	Calibration (2000-2010)	0.87	0.82	5.87
2	Validation (2011-2020)	0.95	0.89	4.62

Note. R^2 =Coefficient of determination, NSE= Nash-sutcliffe efficiency, PBIAS=Percent bias.

Figure 8

The Coefficient of Determination (R²) for Streamflow was Calibrated for the 2000-2010 Period (a) and Validated for the 2010-2020 Period (b)





Watershed-Scale Hydrological Responses to Historical LULC Changes

Table 4 summarizes the responses of key hydrological components—including surface runoff, groundwater flow, lateral flow, water yield, evapotranspiration, and percolation—to historical LULC changes within the SNgW. This study provides a comprehensive evaluation of both the magnitude and direction of hydrological alterations in response to LULC dynamics. Between 2000 and 2010, surface runoff increased by 16.99%, while lateral flow, groundwater flow, water yield, evapotranspiration, and percolation exhibited relative changes of 10.83%, 13.29%, 2.57%, 4.36%, and 10.18%, respectively. A similar pattern was observed from 2010 to 2020, with surface runoff rising by 17.97%. In contrast, lateral flow, groundwater flow, water yield, evapotranspiration, and percolation decreased by 10.01%, 13.48%, 2.07%, 3.68%, and 11.62%, respectively. These declines correspond with the substantial reduction in forested areas and concurrent expansion of agricultural and urban land uses during this period. The observed decreases in percolation, lateral flow, and groundwater flow are likely attributable to diminished infiltration capacity and reduced canopy interception due to vegetation loss, leading to increased conversion of precipitation to surface runoff. Consequently, the transformation of natural landscapes into cultivated and built environments within the SNgW has elevated mean annual surface runoff while suppressing subsurface flow components, thereby significantly influencing watershed hydrological regimes.

Hydrological Responses to Historical LULC Changes at the Sub-Watershed Level

Figures 9 and 10 illustrate the changes in LULC and associated hydrological components at the sub-watershed scale from 2000 to 2020. The southwestern section of the watershed, particularly sub-watersheds 2, 15, and 20, as well as downstream areas including sub-watersheds 27, 29, and 30, which are predominantly characterized by agricultural and settlement land uses, experienced the most pronounced increases in surface runoff during this period. The conversion of deciduous and evergreen forests, miscellaneous lands, and orchards into field crops, paddy fields, and urban/built-up areas significantly elevated surface runoff across nearly all sub-watersheds. This increase in runoff can be attributed to several key factors: steeper slopes in certain sub-watersheds facilitate faster overland flow; soil types with lower infiltration

Table 4

The Mean Annual Values and Relative Changes of the SNgW Hydrological Components Between 2000 and 2020

Hydrological Component (mm)	Hydrological Components Under Simulated Years (mm)			Relative Change of Hydrological Components Between Simulated Years (%)		
	2000	2010	2020	2000-2010	2010-2020	2000-2020
Surface runoff	175.69	197.01	214.36	+16.99	+17.97	+33.21
Lateral flow	68.47	57.64	47.63	-10.83	-10.01	-19.79
Groundwater flow	189.66	174.62	162.89	-13.29	-13.48	-25.43
Water yield	320.56	312.02	307.24	-2.57	-2.07	-4.40
Evapotranspiration	647.21	635.85	637.01	-4.36	-3.68	-7.63
Percolation	210.54	208.64	201.32	-10.18	-11.62	-17.55

capacity reduce water absorption; and urban sprawl introduces impervious surfaces that drastically limit infiltration and increase surface runoff volumes. Notably, sub-watersheds 15 and 30 registered surface runoff increases exceeding 207.92 mm, with 29 out of 30 sub-watersheds demonstrating upward trends. Conversely, groundwater flow exhibited a declining trend in almost all sub-watersheds between 2000 and 2020. The central region of sub-watershed 30 recorded the most substantial groundwater flow reduction, exceeding 163.53 mm, corresponding to its predominant agricultural and settlement LULC characteristics. These findings align with previous research (Aragaw et al., 2021; Tapas et al., 2025), which linked LULC transitions to increased surface runoff and decreased groundwater flow. Additional studies (Faksomboon et al., 2023; Faksomboon & Polthana, 2023; Teklay et al., 2019; Meles et al., 2024; Shekar & Mathew, 2024; Zeydalinejad et al., 2024) corroborate that agricultural expansion, urbanization, and forest cover loss collectively contribute to elevated surface runoff. Furthermore, this study identified that the expansion of field crops, paddy fields, and urban areas corresponded with increased surface runoff coupled with reductions in lateral flow, evapotranspiration, percolation, water yield, and groundwater flow, underscoring the multifaceted hydrological impacts of LULC changes at the sub-watershed level.

Hydrological Responses to Predicted LULC Changes at the Watershed Level

Hydrological responses to anticipated LULC changes were evaluated by comparing projections for 2040 and 2060 against the 2020 baseline conditions. Results indicate that surface runoff is expected to increase substantially (by 32.71%) between 2020 and 2060 (Table 5), predominantly driven by LULC modifications that enhance overland flow pathways. This projected increase highlights the considerable alteration of the watershed's hydrological regime under future land use scenarios. Conversely, declines are forecasted in groundwater flow, lateral flow, water yield, evapotranspiration, and percolation by 21.87%, 22.47%, 3.12%, 3.35%, and 18.42%, respectively. These trends are consistent with findings from comparable studies conducted in the Andassa watershed (2030-2045) (Gashaw et al., 2018), Finchaa watershed (2017-2055) (Dibaba et al., 2020), and Walga watershed (1990-2035) (Tola & Deyassa, 2024), all of which similarly documented increased surface runoff concurrent with reductions in groundwater flow, lateral flow, and evapotranspiration as a consequence of LULC transitions.

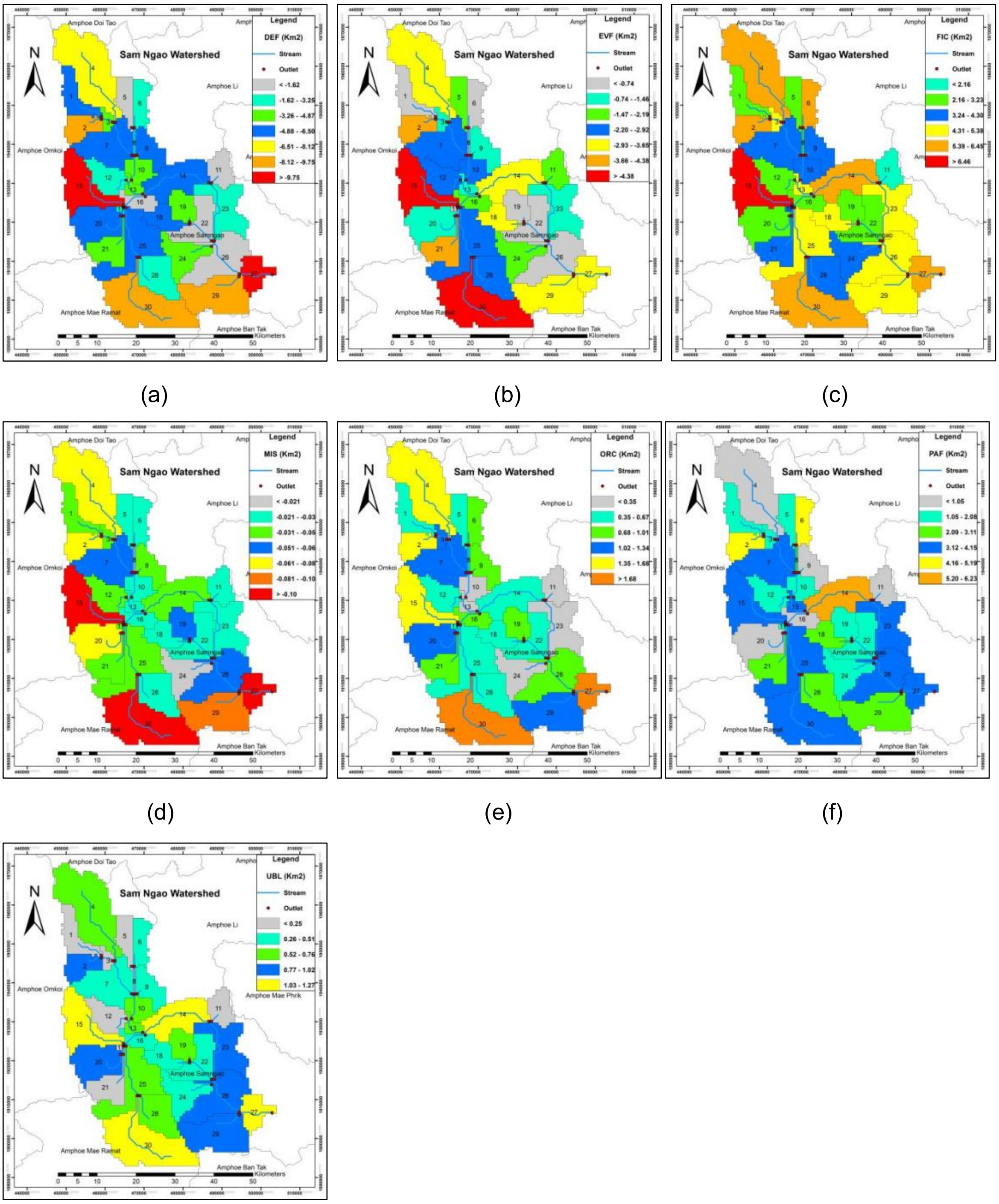
Hydrological Responses to Predicted LULC Changes at the Sub-Watershed Level

The projected LULC changes and corresponding hydrological responses (Figures 11 and 12) reveal pronounced spatial heterogeneity within the watershed. Sub-watersheds 2, 15, 27, 29, and 30 are identified as critical zones, exhibiting substantial increases in surface runoff primarily driven by anticipated expansion of agricultural and settlement areas. Surface runoff is projected to rise steadily, surpassing 229.96 mm by 2060 in these sub-watersheds. Conversely, sub-watersheds 5, 11, 22, and 26 are expected to experience comparatively minor increases, remaining below 187.46 mm. These findings emphasize the spatial variability of runoff dynamics, underscoring the importance of integrating localized land use changes into hydrological impact assessments and watershed management strategies.

A marked decline in groundwater flow is projected across most sub-watersheds, with the greatest reductions concentrated in the central and southern portions. Sub-watershed 30 is predicted to undergo the most pronounced decrease, exceeding 163.53 mm. This trend is strongly associated with sub-watersheds dominated by agricultural and settlement activities, where land use changes have likely diminished infiltration and groundwater recharge rates. Furthermore, evapotranspiration is anticipated to decline, reflecting the combined effects of reduced forest cover and increased agricultural and urban land uses. These observations highlight the complex interactions among land use dynamics, groundwater flow, and evapotranspiration processes within the watershed. A thorough understanding of these interrelationships is essential for effective watershed and environmental management, as well as informed land use planning. Such knowledge facilitates the identification of priority areas for intervention aimed at mitigating water scarcity, promoting sustainable groundwater utilization, and minimizing adverse impacts of LULC changes on the watershed's hydrological regime

Figure 9

Changes in LULC at the Sub-Watershed Levels of SNgW From 2000 to 2020



(a) (b) (c)

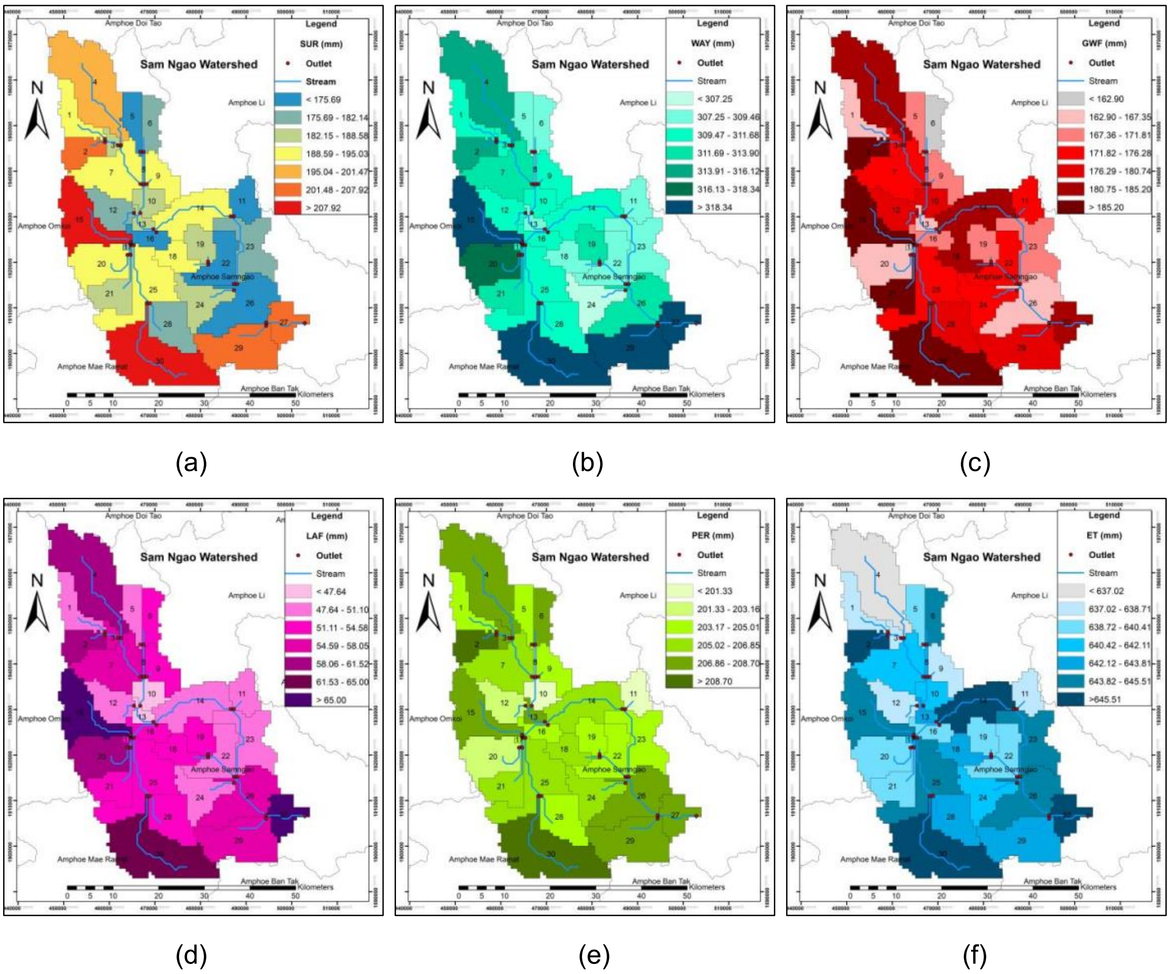
(d) (e) (f)

(g)

Note. DEF = Deciduous Forest (a), EVF = Evergreen Forest (b), FIC = Field crop (c),
MIS = Miscellaneous (d), ORC = Orchard (e), PAF = Paddy field (f), UBL=Urban and built-up land (g).

Figure 10

Changes in Hydrological Components at Sub-Watershed Levels (2000-2020)



Note. SUR = Surface runoff (a), WAY = Water yield (b), GWF = Groundwater flow (c), LAF = Lateral flow (d), PER = Percolation (e), ET = Evapotranspiration (f).

Table 5

Mean Annual and Relative Changes of Predicted Hydrological Components (2020-2060)

Hydrological Component (mm)	Hydrological Components Under Simulated Years (mm)			Relative Changes in Hydrological Components Between Simulated Years (%)		
	2020	2040	2060	2020-2040	2040-2060	2020-2060
Surface runoff	187.45	204.65	238.46	+17.69	+18.54	+32.71
Lateral flow	54.68	50.68	46.59	-9.12	-13.34	-22.47
Groundwater flow	167.41	156.32	148.02	-12.04	-8.64	-21.87
Water yield	310.25	305.68	300.16	-2.13	-2.94	-3.12
Evapotranspiration	627.22	624.14	621.75	-3.01	-2.20	-3.35
Percolation	184.62	167.89	143.28	-13.74	-9.47	-18.42

Evaluation of Streamflow Changes Attributable to LULC Dynamics

Streamflow variations resulting from both historical and anticipated LULC changes were systematically assessed using LULC datasets from 2000, 2010, and 2020 (baseline year 2000), as well as projections for 2020, 2040, and 2060 (baseline year 2020). By comparing these temporal snapshots, the study quantified the impact of LULC transitions on streamflow behavior. The findings, detailed in Table 6, demonstrate pronounced seasonal fluctuations and an average annual streamflow increase of 9.85% over the 2000-2020 period. This increment is primarily driven by the expansion of agricultural and settlement zones coupled with a decline in forest cover.

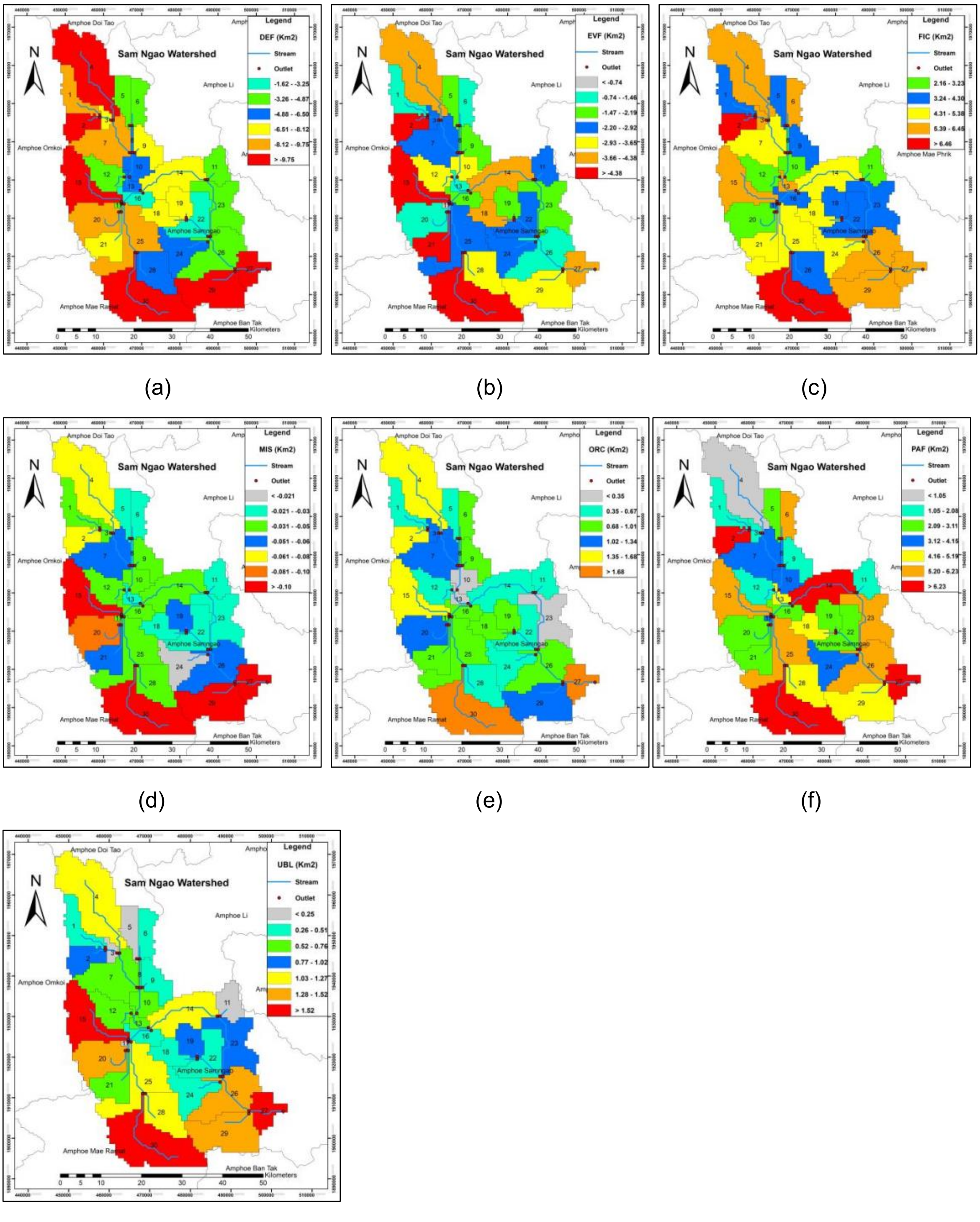
The conversion of forested landscapes into agricultural and urbanized areas exerts significant hydrological effects. Forests generally play a vital role in modulating streamflow through evapotranspiration and canopy interception, mechanisms that enhance water retention and reduce runoff intensity during precipitation events. Conversely, the proliferation of field crops, paddy fields, and built-up urban areas typically results in augmented surface runoff and diminished infiltration rates, thereby altering natural streamflow regimes. These insights underscore the critical need to integrate land use planning with watershed hydrology to sustain water resource availability and ecosystem function.

This finding underscores the critical need for sustainable land management strategies that explicitly consider the hydrological implications of LULC changes on streamflow dynamics. Balancing the pressures of agricultural and urban expansion with the preservation of forest ecosystems is essential to maintain ecological functions and secure long-term water availability within the watershed. Consistently with prior research (Aredo et al., 2021; Doza et al., 2025; Faksomboon et al., 2023; Faksomboon & Polthana, 2023; Kim et al., 2024; Nigusie & Dananto, 2021; Tontisirin & Anantsuksomsri 2021), our results indicate that streamflow increased as a direct consequence of LULC alterations. Specifically, between 2000 and 2020, the average streamflow during the wet season increased by 12.85%, reflecting enhanced surface runoff and water availability linked to the expansion of agricultural and settlement areas alongside forest loss.
Conversely, the average dry season streamflow decreased by 7.36% over the same period, suggesting that LULC changes have modified hydrological responses during drier intervals. This decline is likely attributable to reduced groundwater recharge and diminished water retention resulting from forest conversion to agricultural and urban uses. The influence of LULC changes appears more pronounced during the wet season, where increases in cultivated land and built-up areas, coupled with deforestation, amplify both annual and wet season streamflows. These changes concomitantly suppress evapotranspiration and groundwater recharge, thereby limiting water availability during dry periods. The resultant reductions in dry season streamflow may have significant implications for municipal and industrial water supply, agricultural productivity, and ecosystem sustainability.

Parallel findings across the watershed corroborate the consistent impact of LULC changes on streamflow regimes. Previous studies (Aredo et al., 2021; Chang et al., 2024; Saputra et al., 2025) similarly report decreases in dry season flows and increases during the wet season and attribute these changes to LULC dynamics. Projections for 2020-2060 further indicate an anticipated 17.03% increase in average wet season streamflow, suggesting intensified flows during future wet periods. In contrast, average dry season streamflow is projected to decline by 8.49%, reflecting ongoing challenges in water availability during dry seasons. Additionally, projected average annual streamflow is expected to rise, with relative increases from 9.85% in 2020 to 15.27% by 2060. These trends highlight the profound hydrological consequences of future LULC changes on watershed streamflow patterns, underscoring the imperative to incorporate LULC dynamics into water resource management and planning frameworks to promote sustainable water use and mitigate adverse hydrological impacts.

Figure 11

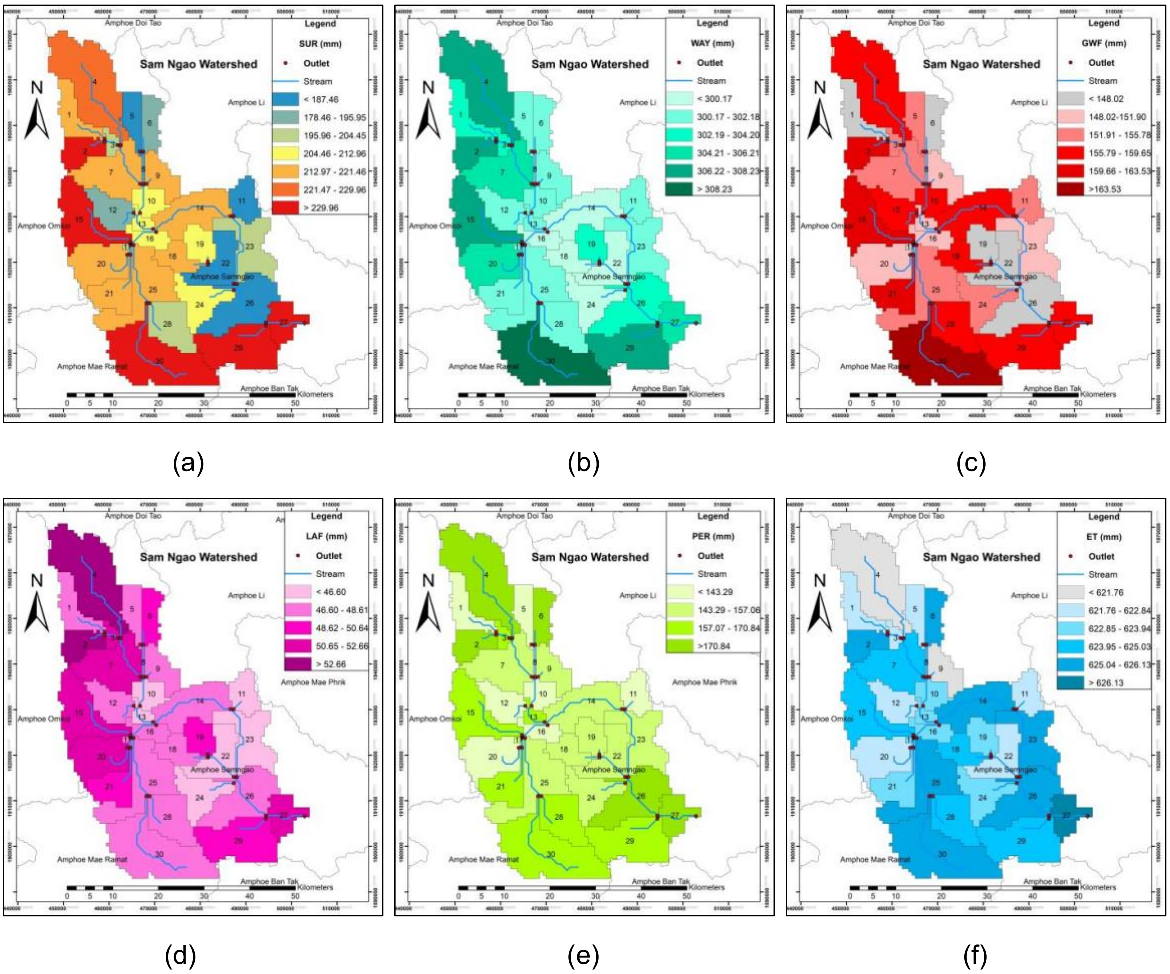
Changes in LULC at the Sub-Watershed Levels of SNgW From 2020 to 2060



Note. DEF=Deciduous Forest (a), EVF= Evergreen Forest (b), FIC=Field crop (c), MIS= Miscellaneous (d), ORC=Orchard (e), PAF= Paddy field (f), UBL=Urban and built-up land (g).

Figure 12

Changes in the Hydrological Components at the Sub-Watershed Level (2020-2060)



Note. SUR = Surface runoff (a), WAY = Water yield (b), GWF = Groundwater flow (c), LAF = Lateral flow (d), PER = Percolation (e), ET=Evapotranspiration (f).

Table 6

Relative Changes in Historical and Predicted Seasonal Streamflow

Stream Flow (m^3/s)	Historical Relative Change (%)			Predicted Relative Change (%)		
	2000-2010	2010-2020	2000-2020	2020-2040	2040-2060	2020-2060
Average annual	5.81	6.47	9.85	6.47	8.69	15.27
Average wet season	7.65	8.31	12.85	9.65	12.46	17.03
Average dry season	-3.14	-5.74	-7.36	-3.18	-6.33	-8.49

Implications for Water Resource Management

Improved Water Allocation

A comprehensive understanding of hydrological responses to historical and anticipated LULC changes is essential for advancing water resource management in the SNgW region. By systematically identifying spatial and temporal variations in water availability driven by LULC dynamics, water managers can devise more targeted and efficient water allocation strategies. This enables the optimal distribution of water resources to satisfy competing demands from agriculture, industry, and domestic use. Moreover, such evidence-based allocation frameworks can alleviate the negative impacts of water scarcity, encourage sustainable water consumption practices, and enhance the long-term resilience and reliability of regional water supply systems.

Watershed Management Planning

The findings provide critical insights to guide comprehensive watershed management within the SNgW. Understanding how LULC changes affect hydrological processes enables the identification of vulnerable zones requiring prioritized interventions. Implementation of management practices such as reforestation, soil conservation, and erosion control can safeguard water quality, regulate streamflow regimes, and reduce the risk of water-related hazards. These strategies are essential to maintaining the ecological integrity and hydrological stability of the watershed. Moreover, adopting adaptive management frameworks that incorporate continuous monitoring and periodic adjustment based on evolving environmental conditions and emerging scientific evidence is crucial for long-term sustainability.

LULC Policy and Regulations

This study underscores the significant hydrological repercussions of LULC changes, reinforcing the necessity for sustainable land management policies. The results can be used by policymakers to formulate and enforce regulations that promote responsible land use practices, thereby minimizing negative impacts on water resources. Key policy measures may include encouraging sustainable agricultural techniques, integrating green infrastructure within urban planning, and advancing conservation initiatives that protect vital water sources. Embedding these policies into broader national and regional planning frameworks will facilitate coordinated and effective land and water resource management.

Stakeholder Engagement and Collaboration

Effective water resource management requires active stakeholder participation and collaboration. Engaging local communities, government agencies, policymakers, and other relevant stakeholders in decision-making processes ensures that sustainable land and water management practices are appropriately designed and successfully implemented. Collaborative governance fosters the development of resilient, inclusive, and equitable water management strategies tailored to the SNgW's unique context. These implications highlight the importance of enhancing participatory approaches to increase the legitimacy, acceptance, and durability of management decisions, ultimately benefiting both current and future generations.

CONCLUSION

This study utilized the SWAT model to comprehensively assess hydrological responses to both historical and anticipated LULC changes within the SNgW watershed, Thailand, spanning a 60-year timeframe from 2000 to 2060. Analysis of the historical period (2000-2020) revealed considerable expansion of agricultural and urbanized areas—including field crops, paddy fields, and built-up land—concurrently with notable reductions in deciduous and evergreen forest cover, miscellaneous lands, and orchards. Projected scenarios (2020-2060) indicate a persistent trend of agricultural growth and further forest depletion, which are likely to intensify prevailing hydrological alterations.

At the watershed scale, LULC alterations between 2000 and 2020 corresponded with a significant increase in surface runoff. Model simulations forecasting future LULC scenarios predict continued surface runoff escalation, accompanied by reductions in groundwater recharge, lateral flow, total water yield, percolation, and evapotranspiration rates. These hydrological shifts are primarily attributable to intensified agricultural activities and forest degradation, highlighting an urgent imperative for integrated land–water resource management frameworks aimed at mitigating detrimental hydrological impacts.

At the sub-watershed scale, spatial heterogeneity in hydrological responses was pronounced, with sub-watersheds undergoing extensive forest loss and intensified agricultural activities experiencing the most marked increases in runoff. In light of these spatially explicit findings, this study advocates for the implementation of sustainable management interventions within the SNgW watershed. Recommended measures include enhanced water conservation techniques, soil erosion control, strategies to reduce surface runoff, integrative land and water resource planning, and the active involvement of local stakeholders in governance and decision-making processes.

Despite the comprehensive modeling and spatial analyses, limitations such as uncertainties in future LULC scenarios and climate variability must be acknowledged. Additional constraints involve the assumption of stationary climate conditions throughout the LULC projection period, parameter uncertainty within the SWAT model, and the CA-Markov model’s reliance on the assumption of transition stationarity, which may inadequately capture the dynamic and non-stationary nature of land use changes influenced by evolving socio-economic and environmental drivers. Future research should incorporate coupled climate land use modeling frameworks to better predict hydrological responses under changing environmental conditions. Additionally, integrating socio-economic drivers and ecosystem service assessments could further enhance the development of adaptive watershed management strategies. From a policy perspective, these findings highlight the critical need for incorporating dynamic land use projections into spatially explicit planning and adaptive water resource policies that can respond to evolving environmental and socio-economic conditions. Specifically, land use planning should prioritize preserving critical forested areas and implementing best management practices in agricultural zones to mitigate adverse hydrological impacts. Water policies must emphasize flexible allocation and conservation measures to sustain water availability under variable future scenarios. For future research, it is imperative to advance multi-disciplinary approaches that combine high-resolution climate projections, socio-economic modeling, and ecosystem service valuation to develop integrated decision-support tools. Furthermore, longitudinal studies assessing the effectiveness of implemented land and water management interventions under changing real-world conditions will be invaluable. Overall, this study underscores the necessity for evidence-based policy-making and collaborative stakeholder engagement to foster resilience and sustainable water resource management in the SNgW and analogous watersheds worldwide.

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