Assessing land use and climate change impacts on agricultural watersheds in developing regions using SWAT for sustainable water management

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Abstract

Agricultural watershed modeling has been widely applied to assess hydrological and water quality responses to land use, land cover change, climate change and best management practices (BMPs) in developing countries. This paper provided narrative-driven regional analyses with limited statistical integration for Soil and Water Assessment Tool (SWAT) model performance, watershed characteristics and BMP effectiveness. By compiling 143 studies published between 2017-2025 using PRISMA research protocol and analyzing the data collection using PICO method, this study offers crucial insights for effective water resource management in agricultural water. Results indicate that medium-sized basins (10,001–100,000 km²) dominate SWAT applications, account for approximately 33% of all studies, significantly exceeding other basin size categories. This study reveals urbanization has significant effects on both water quantity and quality, the coefficient of determination (R^2 = 0.923) indicated a strong correlation of 92.3% between LULC and hydrological changes. Most of the studies reported satisfactory to very good results using SWAT, with the coefficient of determination (R^2) and the Nash-Sutcliffe Efficiency (NSE) more than 0.5 (R^2>0.5, NSE>0.5). Furthermore, the review paper identifies BMP in series combining both structural BMPs and management BMPs for watershed protection and sustainable agricultural practice. This review is the first to provide a cross-climatic, synthesis of SWAT applications in developing countries, explicitly linking basin scale, climate regime, model reliability and BMP effectiveness. Future research should focus on data collection and calibration methods for SWAT modelling, climate change projections and extreme event scenarios and long-term analysis by linking model outputs to sustainable agriculture planning.

Keywords: Best management practice, climate change, hydrological analysis, land use land cover change, SWAT, water quality

Introduction

Agricultural watersheds in developing regions are increasingly affected by the combined pressures of land use land cover (LULC) change and climate change, posing significant challenges for water quality and quantity management (Graciela et al., 2018). Projections indicate a 60% increase in food demand by 2050, necessitating more arable land, leading to aggressive land use changes and intensifying water stress (Boretti & Rosa, 2019). In addition, urbanization and population growth exacerbates LULC changes and alters hydrological process by increasing impervious surfaces, modifying surface runoff, soil erosion, nutrient loss within watershed systems that leading to water scarcity and water quality degradation which are fundamental to agriculture (Guo et al., 2023). At the same time, climate change manifests through shifts in precipitation patterns, rising temperatures and greater frequency of extreme events, which influence crop water demand and soil moisture regimes critical for sustaining productive agriculture (Zhang et al., 2022). The combined land use dynamics and climate stressors may aggravate hydrological imbalances and greater flood and drought risks affecting agriculture productivity. In developing regions, where agriculture remains a primary source of employment and livelihood, it is crucial to design effective water infrastructure and management practices to support sustainable water resources allocation for agricultural productivity.

Ecohydrological models like the Soil and Water Assessment Tool (SWAT) (Srinivasan & Arnold, 1994; Gassman et al., 2007; SWAT, 2019) and SWAT+ (Bieger et al., 2017) are widely used to study interactions between environmental changes and hydrological processes, offering valuable water management insights. The SWAT model addresses hydrological responses and environmental issues across varying spatial and temporal scales (SWAT, 2019). It requires input data like daily precipitation, temperature, a Digital Elevation Model (DEM), LULC maps, soil maps and daily flow records (Tan et al., 2021; Wang et al., 2013). SWAT simulations manage water, sediment, nutrients and chemicals within sub-watersheds and across entire river basins (Wang et al., 2019). The model operates on sub-daily to annual time steps, providing detailed insights into streamflow dynamics at multiple scales (Pan et al., 2020; Tan et al., 2021).

SWAT's popularity has surged since 2009, with numerous applications worldwide, including general reviews (Wang et al., 2019), comparisons with other models (Burigato Costa et al., 2019), specialized reviews (Krysanova & White, 2015; Gassman & Wang, 2015), and specific applications in regions like Southeast Asia, Brazil and Africa (Tan et al., 2019; Bressiani et al., 2015; Akoko et al., 2021). SWAT has also been used to simulate hydro-climatic extremes, sub-daily hydrological processes and rice paddy systems (Tan et al., 2020; Brighenti et al., 2019; Gassman et al., 2022). However, no existing systematic review on SWAT studies have focused on hydrological analysis on the impacts of agriculture watersheds due to LULC change, climate change and a combination of both. Therefore, the findings of this research aim to bridge this gap by compiling and reviewing existing SWAT studies on the watersheds due to LULC change and climate change. The review aims to answer research questions using Problem Intervention Comparison Outcome (PICO) method for researchers (Figure 1). These questions include what can be derived from the SWAT agricultural watersheds analysis? What actions can be taken upon knowing the impacts of LULC change and climate change towards agricultural watersheds? The research problem is there is limited understanding of how hydrological processes influence the agricultural watersheds due to recent changes in land use and projected climate change, and what mitigation plans can be applied. The emphasis for the review is placed on understanding the impacts of land use change from human activities and climate change on hydrological processes

and water resources by using SWAT for agriculture across temporal and spatial scales. Specifically, the objectives of this review are to provide: (i) a short synopsis of selected SWAT studies for agricultural watersheds reported in the recent literature, (ii) to present a summary of LULC change and climate change on agricultural watersheds, (iii) to report findings of selected water quality studies and best management practices (BMPs) studies for agricultural watersheds and (iv) to recommend future directions and needs for agricultural watersheds. Understanding the combined impacts of LULC and climate change is important for sustainable water management for agricultural watersheds because these drivers often act synergistically, enhancing the frequency and magnitude of hydrological impacts. Without such assessments, agricultural water allocation decisions, irrigation planning and watershed conservation strategies may prove ineffective under changing environmental conditions.
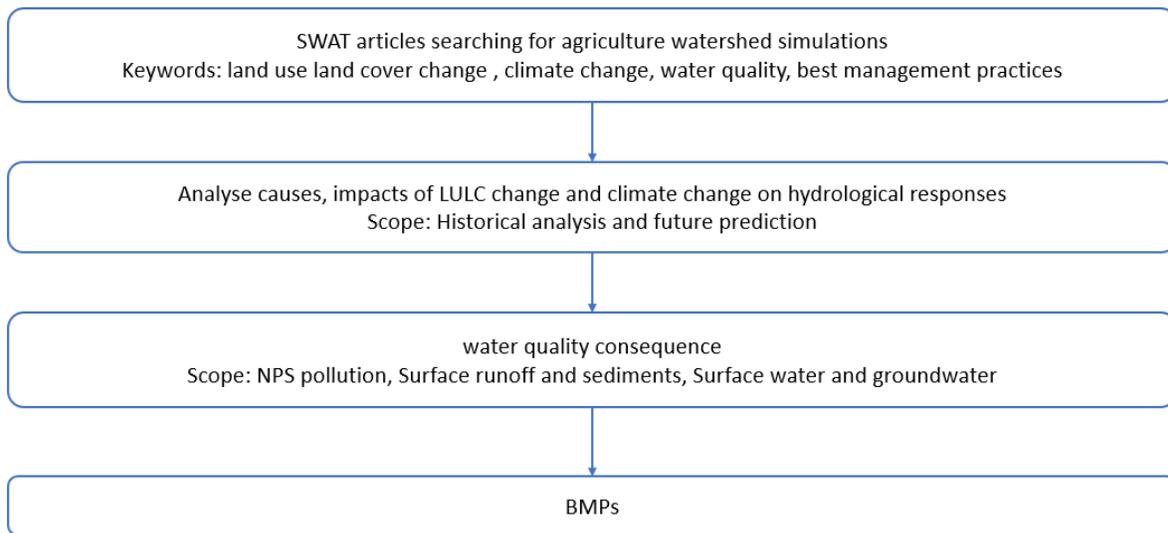

Figure 1. The structure of the systematic review according to PICO method

Research strategy and design

This systematic review followed the Preferred Reporting Items for Systematic reviews and Meta-Analyzes (PRISMA) statement (Page et al., 2021), using a 27-item checklist and flow diagram for search strategy, selection, data identification, extraction and summarization. It synthesizes knowledge on the impacts of LULC and climate change on agricultural watersheds.

Article selection process

Data were collected from multiple databases using keywords and Boolean operators as shown in Table 1. Identified publications were screened for titles, abstracts and full texts based on eligibility criteria, including: i) Hydrologic assessment for agricultural watersheds ii) LULC change and climate change impacts iii) Water quantity or quality impacts iv) BMPs for sustainable water use v) SWAT as the hydrological model.

Table 1. List of search platforms, search queries and search criteria.

Search platform	Search queries	Search criteria
WoS	(TS=(SWAT AND land use change AND agriculture)) OR (TS=(SWAT AND land cover change AND agriculture)) OR (TS=(SWAT AND climate change AND agriculture)) OR (TS=(SWAT AND water quality AND agriculture)) OR (TS=(SWAT AND best management practice AND agriculture))	Include ● Year range: 2017–2025 ● English article only ● Article, review, journal & selected journal ● Relevant keywords
Scopus	(TITLE-ABS-KEY ("SWAT" AND "land use change" AND "agriculture")) OR (TITLE-ABS-KEY ("SWAT" AND "land cover change" AND "agriculture")) OR (TITLE-ABS-KEY ("SWAT" AND "climate change" AND "agriculture")) OR (TITLE-ABS-KEY ("SWAT" AND "water quality" AND "agriculture")) OR (TITLE-ABS-KEY ("SWAT" AND "best management practice" AND "agriculture"))	Exclude ● Conference papers, book chapters, editorial materials, early access ● Duplicate region & desert ● Irrelevant: Dam watershed, hydropower, pollutants assessment only, wheat yield etc.
ScienceDirect	("SWAT" AND "land use change") OR ("SWAT" AND "land cover change") OR ("SWAT" AND "climate change") OR ("SWAT" AND "water quality") AND Agriculture OR best management practice	

SWAT selected studies

Initially, 1524 studies were identified and after following the PRISMA research protocol, 143 studies were shortlisted for qualitative synthesis as in Figure 2.
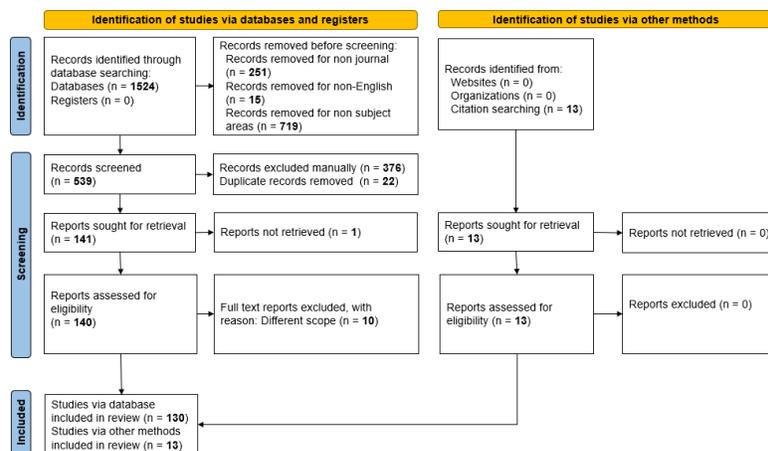

Figure 2. PRISMA flow chart (Page et al., 2021) for systematic literature review

Out of 143 studies, 91 (63%) were conducted in developing countries: 31 (22%) in Africa, 21 (15%) in Southeast Asia, 21 (15%) in East Asia and 18 (13%) in South Asia. This surge in research activity is due to extensive urbanization impacting hydrological cycles and ecosystems. In contrast, there were 20 from North America and 13 from Europe, with fewer studies from South America, the Middle East and Oceania. Research on agricultural watersheds using SWAT is increasing in developing countries because SWAT can simulate water hydrology, impacts of land use changes and/or climate risks and water availability for crops which are important for sustainable agricultural water management planning. International development and research organizations increasingly fund watershed and agricultural research in developing regions, promoting broader applications of SWAT-based modelling. Nevertheless, Asia has variability in research outputs across regions due to data limitations, model adaptation challenges for local cropping systems and fewer specialised SWAT training opportunities in some regions. Countries with stronger research networks and workshops, for example, Vietnam and Thailand show more publications, while others demonstrate comparatively limited research activity.

SWAT applications in agricultural watershed

Overview of systematic review results
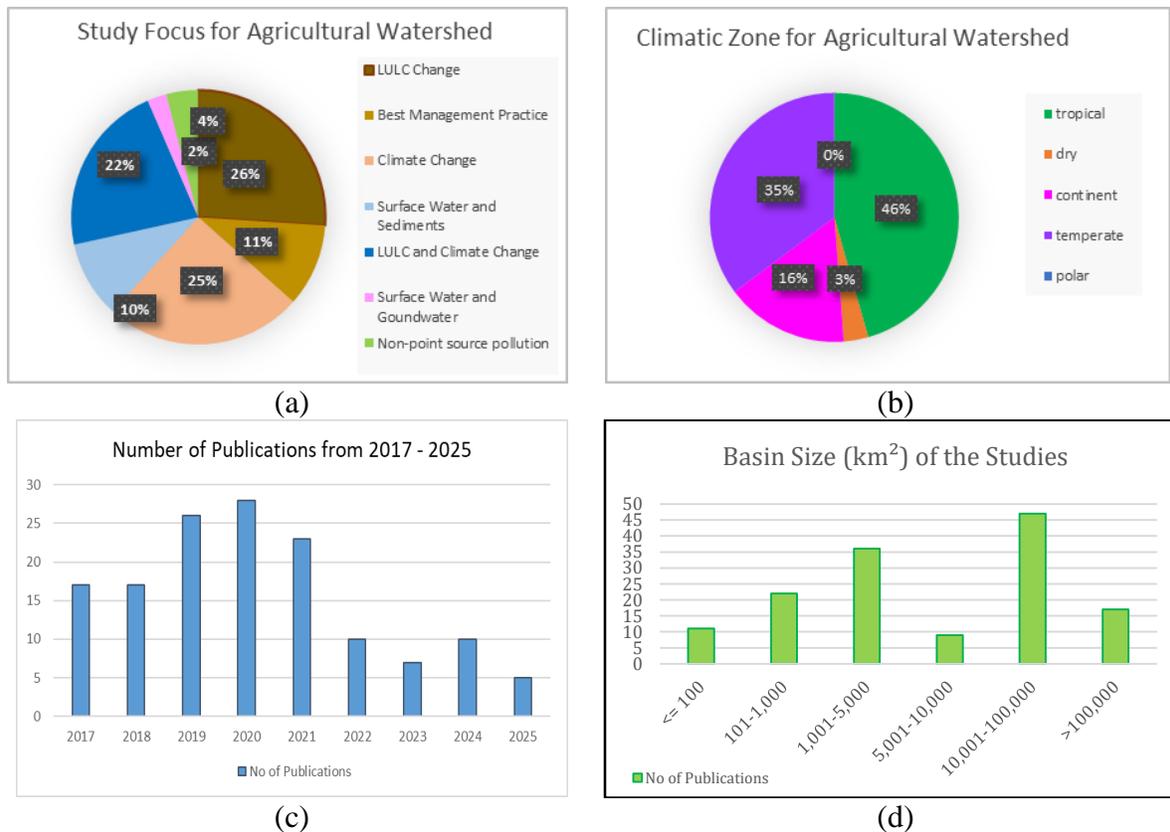

(a)

(b)

(c)

(d)

Figure 3. SWAT publications for Agricultural Watershed based on (a) focus studies, (b) climate zone, (c) year of publication and (d) basin size

Most of the selected articles focus on hydrological assessments related to LULC change (26%) and climate change (25%) (Figure 3a). Other significant areas include water quality assessment (14%) and BMPs (11%) to mitigate water pollution and ensure water security in agricultural watersheds.

Most agricultural watershed studies are from tropical regions (46%), especially Africa and Southeast Asia, with over 50% covering areas larger than 10,000 km² (Figure 3b). Temperate regions account for 35% of studies, primarily from China and Europe. Over half of the studies from China focus on watersheds larger than 10,000 km², while European studies tend to cover smaller areas. In the continental climate zone (16%), studies are predominantly from the United States, covering a range of watershed sizes from 30 km² to 75,000 km². Only 3% of studies are from dry climate regions.

The number of articles published increased significantly from 2019 to 2021 (Figure 3c), with 77 studies (63%), likely due to growing awareness of the impacts of rapid urbanization and LULC changes on water scarcity and pollution. The lower number of identified publications for the period 2022–2025 were relatively lower, reflecting methodological constraints and evolving research trends rather than a decline in SWAT-based watershed research. This apparent reduction is mainly due to publication and indexing delays for recent articles, reduced field campaigns and funding delays post-COVID-19. In addition, the present review applied strict inclusion criteria, focusing exclusively on SWAT applications in agricultural watersheds, which excluded recent shifts from 2022 onwards toward SWAT+, coupled modeling frameworks and data-driven approaches.

SWAT has been applied across a broad range of basin scales, from small watersheds under 100 km² to large basins over 100,000 km² (Figure 3d). Most studies (33%) focus on basins of 10,001-100,000 km², followed by 1,001-5,000 km² (25%) and 101-1,000 km² (15%). Only 8% of studies cover basins smaller than 100 km² and 6% focus on 5,001-10,000 km² basins. The largest study area is the Niger River basin (2,250,000 km²), followed by the Amur River Basin (2,000,000 km²) draining over China, Russia, Mongolia and North Korea. The smallest basins studied are the Matny mountain catchment (3 km²) in Poland and the Semra watershed (4 km²) in India.

A substantial proportion of the reviewed studies were carried out in basins with areas ranging from 10,001 to 100,000 km². This size reflects the suitability for regional climate and land-use patterns, yet small enough to avoid excessive spatial heterogeneity and parameter uncertainty associated with very large basins. Moreover, the availability and resolution of climatic and land-use data and management relevance are more compatible with regional-scale analyses.

SWAT statistical evaluation for agricultural watershed

Calibration and validation in SWAT are performed using the SWAT-Calibration and Uncertainty Program (SWAT-CUP), an integrated method of the SWAT model (Pan et al., 2020). Two key statistical measures for SWAT's calibration and validation are the coefficient of determination (R^2) and the Nash-Sutcliffe Efficiency (NSE) (SWAT, 2019). Successful calibration demonstrates SWAT's reliability as a hydrological model, even in data-scarce basins (Burigato Costa, 2019).

Table 2. The range of statistical values reported for SWAT stream flow calibration and validation by region

Region	Yearly/ Monthly/ Daily			
	Calibration		Validation	
	R²	NSE	R²	NSE
North America	0.51-0.93	0.50-0.95	0.50-0.92	0.60-0.96
South America	0.55-0.97	0.51-0.93	0.60-0.86	0.57-0.85
Europe	0.69-0.97	0.77-0.86	0.57-0.97	0.73-0.92
Africa	0.63-0.88	0.62-0.89	0.50-0.91	0.50-0.91
East Asia	0.65-0.88	0.58-0.86	0.60-0.88	0.62-0.85
South Asia	0.63-0.94	0.61-0.96	0.61-0.93	0.56-0.96
West Asia	>0.60	>0.50	>0.80	>0.60
Middle East	0.50-0.60	0.55-0.75	0.50-0.70	0.41-0.69
Southeast Asia	0.76-0.93	0.72-0.92	0.66-0.94	0.61-0.92
Transnational	0.65-0.85	0.60-0.88	0.62-0.84	0.51-0.84
Oceania	>0.90	>0.90	>0.90	>0.90

Most of the 143 studies used R² and NSE to evaluate SWAT's reliability for scenario analysis. These measures compared SWAT simulated streamflow values to measured values over yearly, monthly and daily periods, with aggregated yearly and monthly statistics based on daily values. Generally, R² and NSE statistics from the reviewed studies exceeded 0.5, meeting the thresholds for satisfactory simulations (Moriasi et al., 2015) and criteria for "satisfactory" to "very good" streamflow simulation results (Moriasi et al., 2007).

SWAT performance ranged from satisfactory to very good for agricultural watershed studies in North America, South America, East Asia and South Asia and good to very good in Europe. SWAT also performed well in most African regions and demonstrated good to very good results in Southeast Asia. While studies in West Asia, the Middle East and Oceania were limited, SWAT showed reasonably good performance in Oceania and reliable performance in West Asia and the Middle East.

Analysis of selected agricultural watershed simulations

a) Agricultural watershed simulations analysis according to geographical regions

Researchers globally have employed the SWAT model utilizing dynamic land use to investigate the impacts of LULC changes on hydrological components, revealing significant alterations in basin hydrology (Affessa et al., 2023; Aredehey et al., 2020; Teklay et al., 2019). For instance, notable studies include those conducted in North America and in Europe, where the Mississippi Big Sunflower River Watershed, the Middle Chattahoochee watershed and the North Johnstone River exhibited increased river flows due to urbanization and agricultural expansion (Gay et al., 2025; Nepal et al., 2023; Ni et al., 2021; Zhang et al., 2020). African studies, particularly in the Upper Blue Nile Basin, underscore the benefits of reforestation for water security, highlighting the region's potential for increased groundwater and dry season base flow when forested areas expand (Kenea et al., 2021; Da Silva et al., 2018). Group studies in Asia, reported that the Muda River Basin, the Wei River Basin, the Palas Basin, the Semra Basin and the Lam Pachi Basin indicates

that urbanization and dense forest cover impact streamflow and surface runoff, with agricultural practices further modifying hydrological responses (Khadka et al., 2023; Hu et al., 2021; Kositsakulchai et al., 2021; Tan et al., 2021; Tankpa et al., 2021; Azgin and Celik, 2020; Mishra et al., 2017). Comparative analyses of different land use scenarios in East Asia revealed that forest-prone landscapes result in decreased water yield and surface runoff, while agriculture-rich landscapes lead to increases in both due to irrigation activities (Kim et al., 2024; Ware et al., 2024; Zhang et al., 2023; Sun et al., 2017).

b) Agricultural watershed simulations analysis according to climatic zone regions

Studies across various climatic zones using the SWAT model consistently indicate that climate change significantly impacts hydrological systems, often in conjunction with LULC changes. In addition, the impacts of climate change are often amplified by the elevation, area and slope aspects of catchments, affecting annual streamflow and sediment yield transport. Rising temperatures and declining precipitation generally lead to increased evapotranspiration (ET), higher surface runoff, decreased overall water yield, decreased groundwater recharge and heightened hydrological extremes across the tropical climate of Sub-Saharan Africa and Southeast Asia. (Gebrie et al., 2024; Khadka et al., 2023; Ngondo et al., 2022; Mengistu et al., 2021; Li and Fang, 2021; Naschen et al., 2019b). Due to precipitation changes in tropical and subtropical monsoon climates, the Nowrangpur basin, the Ravi River basin and the Upper Baitarani River basin studies in South Asia, show that applying deficit irrigation can save significant water, though it may slightly reduce crop yields (Kaur et al., 2025; Ullah et al., 2024; Uniyal et al., 2019).

Agricultural watershed simulations in the Mekong River Basin and its major tributaries in Southeast Asia reveal consistent transboundary patterns shaped by monsoonal climate, intensive agriculture and upstream–downstream interactions (Khadka et al., 2023; Sridhar et al., 2019). Precipitation variability increases are projected for humid subtropical and tropical savanna climate zones due to climate shifts in South America (Abou et al., 2022), so does the same projected trend for Mediterranean and continental climates in Asia and Europe (Tezel et al., 2025; Keleş et al., 2024).

In the temperate climate zone, mostly studies conducted in North America and Europe have highlighted the significant impact of climate change on nutrient transport, soil moisture dynamics and the effectiveness of agri-environmental measures. Aliyari et al. (2021) examined the South Platte River Basin and Suttles et al. (2018) studied the Yadkin-Pee Dee Basin in the United States found that increased temperature and reduced precipitation, leading to a decline in groundwater storage and crop yield. Molina et al. (2018) studied the Odense Fjord watershed in Denmark indicated that climate-specific scenarios could significantly impact on nitrate pollution depending on land use and BMPs. Across SWAT agricultural watershed simulations in North America and Europe, land-use change alone tends to produce moderate hydrological responses due to relatively stable land-cover patterns and widespread implementation of conservation practices. In East Asia, Ji et al. (2022) and Zhang et al. (2019a, 2019b) reported a positive relationship between net vegetation productivity and hydrological flows in the Nansi Lake Basin and the Zhenjiangguan Basin respectively. The Anyang Basin study by Ware et al. (2024), the Yihe River study by Li et al. (2020) and the Upper Sang-kan Basin study by Zhang et al. (2017) revealed the same streamflow pattern.

In the Continental Climate Zone, agricultural watershed simulations, for instance, the Hamilton Harbour watershed (Dong et al., 2021), the Salt River Basin (Phung et al., 2019) and the

Upper Narew and Barycz watersheds (Marcinkowski et al., 2017) in North America and Eastern Europe reveal strong sensitivity to temperature-driven processes such as snow accumulation, snowmelt and frozen soils. In Asia, Zhou et al. (2021) found that local LULC changes significantly influenced water usage methods, precipitation patterns and vegetation growth in the Amur River Basin. Additionally, studies on the Lhasa River Basin indicated that temperature increases primarily drove changes in streamflow and sediment load (Tian et al., 2020), whereas precipitation was the most sensitive factor in the Zhenjiangguan Watershed (Zhang et al., 2019a).

Combined scenarios of intensive agricultural land use and climate change studies demonstrate complexities in hydrological responses that further exacerbate hydrological extremes, streamflow variability and nutrient transport for predominate tropical climate in most Southeast Asian countries and African countries; similarly, the monsoon climate in South Asian countries comparable patterns (Gebrie et al., 2024; Khadka et al., 2023; Chim et al., 2021; Sujarwo et al., 2021; Sinha et al., 2020; Trang et al., 2017). When comparing climate change and LULC change, most studies reveal climate change is the dominant driver of hydrological changes (Amiri et al., 2023; Khadka et al., 2023; Getachew et al., 2021; Naschen et al., 2019a), but there are simulations show otherwise (Nepal et al., 2024; Abou et al., 2022; Ngondo et al., 2022; Kiprotich et al., 2021).

c)   Agricultural watershed simulations analysis on water quality

Research employing the SWAT model to analyze agricultural watershed simulations has consistently highlighted that water quality responses are governed by the interaction between agricultural management practices, hydrological processes and climatic variability. Key studies demonstrate that agricultural expansion leads to increased soil erosion and sediment accumulation in watersheds, with forested areas generally maintaining better water quality (Gay et al., 2025; Nepal et al., 2024; Halecki et al., 2018; Sinha & Eldho, 2018; Mello et al., 2017). For instance, the Kaduna Basin in Nigeria, the Anzali wetland catchment in Iran, the St. Clair-Detroit River Basin in North America and the Upper Blue Nile Basin study in Ethiopia showed that nutrient export and sediment primarily originated from agricultural sources (Daramola et al., 2022; Aghsaei et al., 2020; Dagnew et al., 2019; Ayele et al., 2017). Furthermore, studies in the Wilmot River Watershed in Canada and the Flumen River in Spain underscore the critical role of land use and farm practices in mitigating nitrate pollution, emphasizing the need for appropriate irrigation and fertilization practices to reduce non-point source pollution (Liang et al., 2020; Sorando et al., 2019). Coupled modeling approaches, such as SWAT with HEC-RAS in the Xiaoqing River Basin, have effectively simulated water quantity and quality, revealing that rapid land use changes for new settlements exacerbate non-point source pollution and sediment dynamics (Xue et al., 2021).

Both surface water and groundwater are affected by excessive nutrient levels, if there are high rates of fertilizer application and inadequate irrigation practices in places with intensive agricultural activities (Beeram et al., 2024). Shawul et al. (2019) applied partial least squares regression components in SWAT simulations and the results indicated that the reduction of groundwater was mainly due to urbanization, whereas the change in forest area enhanced groundwater. The finding provided an insight that groundwater was strongly associated with the forest areas, lateral flow was highly correlated with pasture and surface runoff was significantly attributed to the urban and cropland changes. Akbari et al. (2022) explored water use optimization and groundwater management in the Eshtehard watershed for the agricultural crops in a water scarce area in Iran. They learnt that the optimum crop pattern, for example, winter barley to replace winter wheat and cotton crops, helped to reduce irreversible damage to groundwater depletion in

the optimum state. Another study by Liang et al. (2020) found that groundwater was identified as the dominant source of nitrate loading for growing and non-growing seasons.

d) Agricultural watershed simulations analysis on best management practice

Research using the SWAT model on best management practices (BMPs) in agricultural watersheds aims to reduce water pollution and improve water resource management. Malhotra et al. (2018) used sediment fingerprinting with SWAT to identify sediment hotspots, recommending targeted BMPs for effective sediment reduction. There are two types of structural BMPs and management-based BMPs. Structural BMPs including buffer strips, terracing and sediment retention structures, shown to have the greatest impact in reducing sediment loads and peak runoff, particularly in erosion-prone watersheds. Himanshu et al. (2019) evaluated BMPs in India's Marol watershed, finding conservation tillage, contour farming and filter strips effective in reducing sediment yield and nutrient losses.

In contrast, management-based BMPs, including optimized fertilizer application, reduced tillage and crop rotation, demonstrate stronger impacts on nutrient reduction than on hydrological response. Salmoral et al. (2017) showed that afforestation in Spain's Genil River Basin reduces water pollution and increases soil water retention. Liu et al. (2022) identified wetland restoration and fertilizer management as effective BMPs for reducing nutrient loads in Canadian Prairies Watersheds. Merriman et al. (2018) found reducing fertilizer and irrigation effective for lowering dissolved reactive phosphorus in the Eagle Creek Basin in the United States. Sith et al. (2019) reported significant sediment reduction with land cover conversion and mulching in Japan. Maydana et al. (2020) found conservation agriculture the best option for reducing pollution in Argentina's Carcarana River Lower Basin. Zettam et al. (2022) from Africa emphasized the benefits of conservation practices like contour farming and strip cropping for pollution reduction.

On the other hand, Jamshidi et al. (2020) and Liu et al. (2019) found that BMPs in series were more effective in reducing pollutant loads. Jamshidi et al. (2020) applied vegetated filter strips as structural BMP to reduce phosphorus, while fertilizer and irrigation management as management BMP to reduce nitrogen in the Zrebar Lake basin and found BMPs are most effective when strategically targeted, climate-adapted and combined, rather than implemented as isolated measures.

Key findings and discussion

Analysis of agricultural watershed simulations for this review across developing countries demonstrates distinct patterns influenced by geography, climate, land-use practices and data availability. Urban expansion in developing countries driven by population growth and migration significantly impacts LULC, affecting hydrological components and freshwater supply.
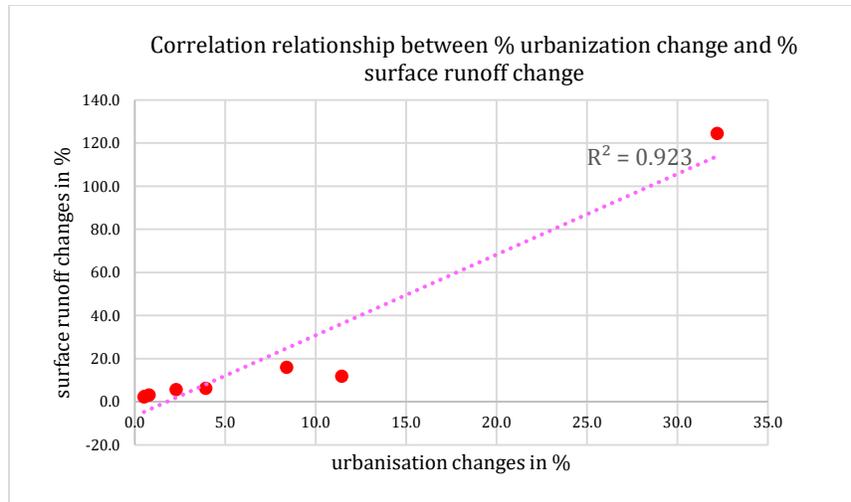
Source: Wang et al., 2018; Zhang et al., 2020; Awotwi et al., 2019; Kundu et al., 2017

Figure 4. Correlation relationship between % urbanization change and % surface runoff change

Different land uses affect water distribution components spatially and temporally. The synthesizing results of the studies show a strong correlation between land use changes and hydrological processes and there is a linear relationship of the coefficient of determination (R^2) 0.923 between urbanisation and increased surface runoff (Figure 4). This review highlights that urbanization influences water balance and hydrological components including surface runoff, precipitation, ET, interception and infiltration (Garg et al., 2017; Garg et al., 2019); while forest cover reduces it and enhances water yield. Agriculture and grassland have mixed effects on water storage capacity. Soil, groundwater and vegetation significantly influence surface runoff (Tudose et al., 2021). The trend of annual streamflow declines when there is an expansion of forest area, agriculture land and grassland. Thus, many authors recommend reforestation to ensure water security.
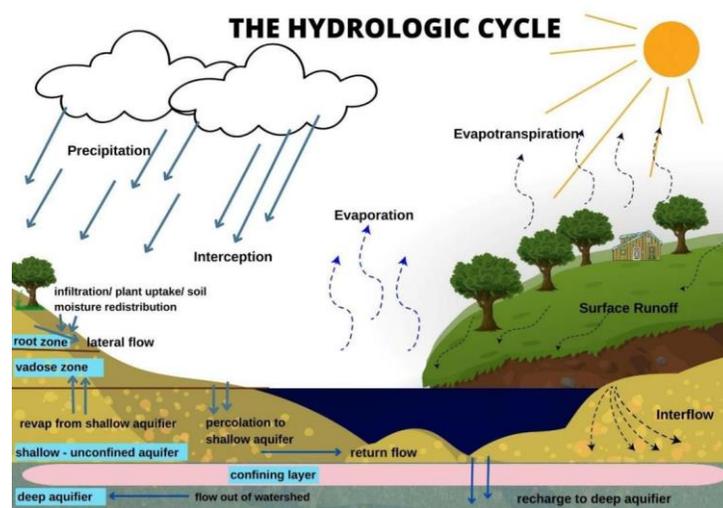
Source: picture is modified from SWAT, 2019 and EPA, United States

Figure 5. The hydrologic components for a watershed

Human-induced LULC changes are main drivers of climate change and changes in atmospheric gases (Tolle et al., 2020; Niu et al., 2019). The entire water balance alters with land use changes (Chemura et al., 2020; Garg et al., 2017) and land use changes alter soil moisture and vegetation within watersheds, affecting groundwater recharge (Zhang et al., 2020) Reviewed articles suggest LULC change induces climate change by influencing land surface temperature and reducing precipitation, driving the hydrological cycle and the hydrologic components of a watershed as illustrated in Figure 5 temporally and spatially (Aik et al., 2021; Zhang & Zhou, 2021; Garg et al., 2017). Studies show that land use coupled with conservation practices helps reduce annual discharge and water yield. Some authors in this reviewed article found climate change is the dominant driver causing an increase in temperature and a decrease in annual precipitation, leading to changes in hydrological processes and a decline in crop yield (Aliyari et al., 2021; Mengistu et al., 2021; Pulighe et al., 2021; Worku et al., 2021; Zou et al., 2020; Luo et al., 2019; Tsvetkova & Randhir, 2019). Nevertheless, there was no consensus from the reviewed studies on whether climate change or LULC change was the dominant factor affecting hydrological impacts, as findings were often contradictory. The relationship between climate change and LULC change in affecting hydrological processes is complex and multidirectional.

Across developing countries, we found SWAT simulations predominantly focus on runoff, sediment yield and nutrient export in tropical and semi-arid basins in Sub-Saharan Africa. Due to data scarcity limitations in the African region, most studies have to rely on SWAT with global or coarse-scale datasets, leading to higher uncertainty in both hydrological and water quality predictions. Whereas, In Southeast Asia and South Asia, irrigation and reservoir management significantly influence seasonal streamflow and nutrient transport in rice-dominated basins. Thus, mostly studies in this tropical monsoon region focusing analyses of agricultural watershed simulations on flooding, nutrient management and irrigation impacts. While data availability in Asia is higher than in Sub-Saharan Africa, studies often neglect extreme events and cumulative impacts, which are increasingly relevant under climate change. Compared to Africa and Asia, modeling efforts in South America are relatively advanced due to long-term monitoring programs, for example, simulations conducted in the Upper Paraná Basin, allowing for robust calibration of SWAT models and high accuracy of simulation results. Agricultural watershed simulation studies in North America and Europe are characterised by a strong focus on assessing water quality degradation, water harvesting structures to increase green water availability and maintain blue water levels, nutrient dynamics, BMPs and policy-relevant assessments for agricultural productions.

SWAT is effective for modeling complex hydrological processes in watersheds, especially in data-scarce regions. However, the synthesis of the review revealed both significant strengths and persistent limitations encountered during hydrological modelling that influence the reliability and applicability of model outcomes. SWAT generally demonstrates satisfactory performance in simulating streamflow, particularly at monthly and annual time scales across developing countries. SWAT-based water quality studies consistently show that sediment and phosphorus loads are closely linked to surface runoff and erosion processes, while nitrogen dynamics are more sensitive to fertilizer application, irrigation and subsurface flow pathways. Despite these insights, uncertainty in water quality simulations remains high. SWAT primarily simulates static land use and land cover patterns, but it may not adequately account for the increased sediment and nutrient loads generated during LULC transitions, such as those occurring during construction phases for settlement development. Additionally, the SWAT model does not incorporate sediment and nutrient contributions from stream bank erosion, which is a crucial factor to consider in long-term

LULC change simulations, particularly when assessing non-point source pollution. The authors highlighted that contradictory results exist regarding urban expansion's impact on runoff, highlighting the need for meta-analyses to resolve these discrepancies and improve model performance.

Conclusions and future directions

Water sustainability is critical for rain-fed agriculture in developing countries. Many developing countries face intensifying water scarcity, unpredictable rainfall and food security challenges, especially under climate change. Agricultural watershed simulations using SWAT demonstrate that climatic conditions primarily govern hydrological responses, particularly in tropical and semi-arid regions. On the other hand, land management and BMP implementation dominate nutrient and sediment mitigation especially in temperate and mediterranean climates across developing countries. Strategic application of BMPs including targeted, in series or regionally optimized are essential to improve water quality under diverse environmental conditions.

SWAT's ability to integrate climate scenarios with land-use dynamics makes it a preferred tool for understanding future water resource scenarios in agricultural landscapes. Nevertheless, data limitations, inconsistent modeling of extreme events and inadequate groundwater representation remain critical challenges across developing countries. Despite the limitations, SWAT simulation results help policymakers and farmers develop adaptation strategies, improve irrigation planning and implement sustainable practices. Future research on agricultural watershed simulations in developing countries should prioritize enhancing model realism and data quality under realistic socioeconomic constraints. First, greater emphasis should be placed to improve frameworks for validating climate product reliability and consider local effects like urban heat and rainfall, specifically improving data collection and calibration methods. Specific analyses on key crops and their impact on water quality are essential for sustainable management. Second, how climate and land-use changes affect water quality and assess cumulative effects of multiple BMPs to mitigate pollution should be more explicitly represented in the model. Third, climate change projections and extreme event scenarios are essential to assess long-term watershed resilience and sustainable water management. Finally, long-term analyses and linking model outputs to provide insights into potential streamflow and water availability for sustainable agricultural planning and better management practices.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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33

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