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Article

Hydrological response to land use/land cover projection in Cisadane watershed, Indonesia

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Abstract: The Cisadane Watershed is in a critical state, which has expanded residential areas upstream of Cisadane. Changes in land use and cover can impact a region's hydrological characteristics. The Soil and Water Assessment Tool (SWAT) is a hydrological model that can simulate the hydrological characteristics of the watershed affected by land use. This study aims to evaluate the impact of land use change on the hydrological characteristics of the Cisadane watershed using SWAT under different land use scenarios. The models were calibrated and validated, and the results showed satisfactory agreement between observed and simulated streamflow. The main river channel is based on the results of the watershed delineation process, with the watershed boundary consisting of 85 sub-watersheds. The hydrological characteristics showed that the maximum flow rate (Q max) was 12.30 m^3/s, and the minimum flow rate (Q min) was 5.50 m^3/s. The study area's distribution of future land use scenarios includes business as usual (BAU), protecting paddy fields (PPF), and protecting forest areas (PFA). The BAU scenario had the worst effect on hydrological responses due to the decreasing forests and paddy fields. The PFA scenario yielded the most favourable hydrological response, achieving a notable reduction from the baseline BAU in surface flow, lateral flow, and groundwater by 2%, 7%, and 2%, respectively. This was attributed to enhanced water infiltration, alongside increases in water yield and evapotranspiration of 3% and 15%, respectively. l Therefore, it is vital to maintain green vegetation and conserve land to support sustainable water availability.

Keywords: hydrological characteristics; LULC; sustainable development; SWAT model

1. Introduction

A watershed is a geographical unit of combined terrestrial and aquatic ecosystems (Cao et al., 2022), which provides several benefits, such as providing and regulating water resources (de Groot et al., 2002). There are complex interactions between water, soil, climate, and vegetation within watersheds to support the capture and distribution of water (Rodríguez-Morales et al., 2023). One of the most significant watersheds in Indonesia because of its location in the densely populated Greater Jakarta Area is the Cisadane watershed. It is home to approximately 1.7 million people. It serves as a source of clean water for agriculture, animal husbandry, industries, and raw water supply for Municipal Waterworks (PDAM), a regional water utility company (Gumelar et al., 2017).

However, the Cisadane watershed faces numerous challenges primarily due to land use conversion activities, which disturbs the natural balance of ecosystems. This activity escalates alongside population growth, urbanization, and industrialization (Putra et al., 2021). Uncontrolled and unsustainable land use in the upstream areas of this watershed, which are protected areas, has caused serious ecological damage and has harmed the middle and the downstream areas (Endang and Tessie, 2014). These problems lead to significant degradation of watershed quality. According to a report from the Ministry of Environment and Forestry 2015 (KLHK, 2015), the Cisadane watershed is one of 15 priority watersheds that require immediate restoration.

Land use and land cover change (LULC) is a crucial factor determining changes in catchment hydrological processes, as it affects the water cycle in several ways (Luo et al., 2020). Numerous studies have been conducted to evaluate the impacts of land use on water resources (Balist et al., 2022; Kayitesi et al., 2022; Memarian et al., 2014). These studies have shown that land use conversion can significantly alter hydrological processes, such as evapotranspiration, interception, and infiltration, which can lead to spatial and temporal changes in surface and subsurface flow patterns. The shift from vegetation to non-vegetation areas in the river basin due to rapid development activities led to significant changes, such as an increase in flow discharge, extreme discharge fluctuations between seasons, fluctuations in surface flow coefficients, river overflows during the rainy season, and drought during the dry season (Maru et al., 2023). It is essential to represent land-use dynamics in agro-hydrological models because land-use change can affect water supplies.

Modelling tools are currently being developed and implemented to integrate various components that constitute natural and human-modified landscapes to assess hydrological processes as a provider of ecosystem services in watersheds (Bagstad et al., 2013). The integrated nature of the hydrological model combining vegetation, soil, water, management, and weather components of landscapes, serves as a comprehensive approach to estimating several variables that can be interpreted as ecosystem service (ES) (Francesconi et al., 2016). Several researchers have focused on watershed hydrological characteristics and models, such as creating a hydrological simulation model for rural watersheds in China (Varga et al., 2016) and hydrological modelling in the Thamirabarani sub-watershed in India (Kaliraj et al., 2023). Many models have been developed to model hydrology, including the ParFlow Hydrological model (Carlotto et al., 2023), the Hydrologic Engineering Center's Hydraulic model (Castro and Maidment, 2020), and the Large-Scale Distributed Hydrological model (Pontes et al., 2017). The SWAT model provides advantages compared to other models, including the fact that the results of the hydrological model are depicted graphically and can project changes in hydrological characteristics (Saez et al., 2022).

Various strategies can be implemented to minimize the adverse effects of land use change on watershed hydrological responses. These include ecosystem conservation and restoration, adopting sustainable land use practices, and implementing integrated water resource management. Land use planning can effectively mitigate future risks associated with changes in land use cover (Memarian et al., 2014). Coupled models are typically used to provide insight into land use change impacts on hydrological processes. A Markov Chain model and a Dynamic Conversion of land use are used to simulate future land uses, and the SWAT model is used to simulate hydrological processes to quantify the hydrological impacts of land use changes. The study aims to investigate the hydrological impacts of land-use changes in the Cisadane watershed using the SWAT model, which addresses the following key objectives, such as quantifying the effects of land-use changes on hydrological components, assessing the implications of these changes for watershed management and proposing actionable recommendations for sustainable land-use planning.

2. Materials and methods

2.1. Study area

The research was conducted in the Cisadane watershed in West Java and Banten Province, Indoneia at 106°20′50″–106°28′20″ E and 6°0′59″–6°47′02″ S (**Figure 1**). Cisadane River is the main river in this watershed, subbed from Mount Gede and flowing 126 km into the Java Sea, passing several regencies and municipalities specifically Bogor Regency, Bogor Municipality, Tangerang Regency, South Tangerang Municipality, and Tangerang Municipality. The Cisadane watershed spans an area of 151.126 ha and experiences a mean annual rainfall ranging from 2000 to 5000 mm. As located in a tropical climate zone, the Cisadane watershed has a temperature range of 20 °C–34 °C. This watershed has diverse landscapes and topography. The upper part is dominated by mountains with a slope of up to > 40%, the middle is undulating, and 0%–8% overlooks the lower flat area. The watershed comprises various soil types, including Andosols, Cambisols, Fluvisols, Lithosols, Nitosols, and Regosols.

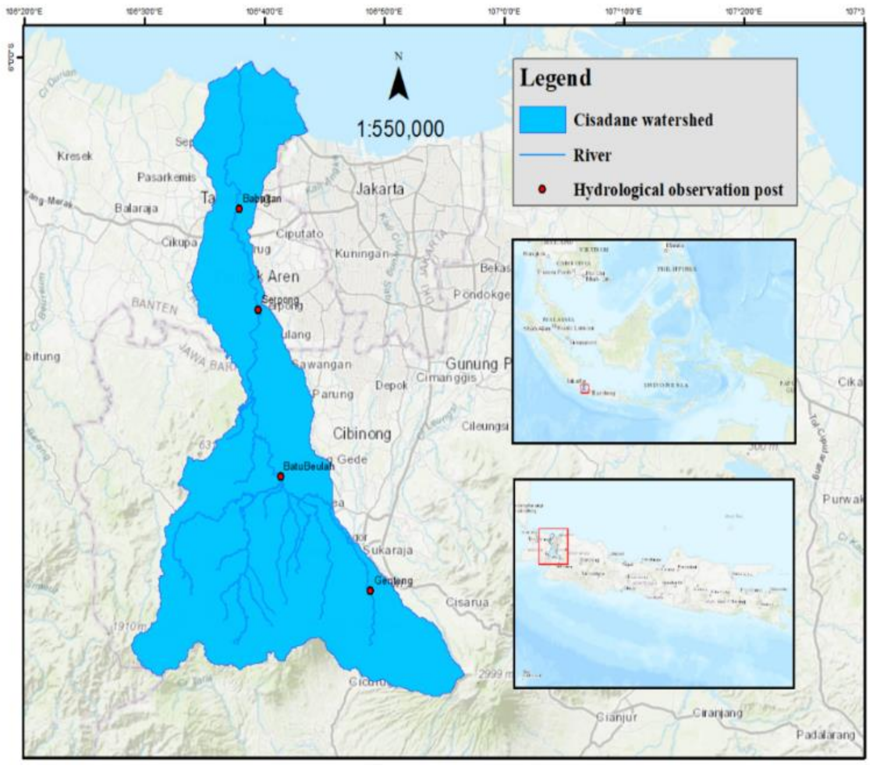

Figure 1. Study area, Cisadane watershed, Indonesia.

2.2. Methods

The study utilized spatial Digital Elevation Model (DEM) data with a resolution of 30 × 30 m for the Cisadane area from USGS, land cover and use projection in 2030 and 2050 (Ambarwulan et al., 2023), Climatological data from NASA POWER, soil type from the Center for Research and Development of Agricultural Land Resources (BBSDLP), as well as rainfall and river discharge data from BBWS Ciliwung Cisadane (Big Agency for River Basin) (**Table 1**).

Table 1. Matrix of research methods.

No.		Data type	Sources and methods of data collection	Data analysis method	Output
1.	a	DEM data	USGS, BBWS Ciliwung-Cisadane, NASA POWER, BBSDLP	ArcGIS, SWAT	Hydrological Characteristics
	b	River discharge and rainfall data			
	c	LULC map			
	d	Climate data			
	e	Soil type data			
2.	a	LULC map	The analysis results of hydrological characteristics		Scenario of changes in hydrological characteristics
	b	Hydrological characteristic data			

The SWAT is a comprehensive, continuous, and physically grounded model designed to simulate various water management scenarios (Arnold et al., 1998). In this study, the SWAT model, which is a physically based semi-distributed model, was utilized to project hydrological responses for 2030 and 2050 across three scenarios. The model divides a catchment into sub-catchments and then further into hydrological response units (HRUs) for which a land-phase water balance is calculated. SWAT defines the hydrological water balance using Equation (1) (Neitsch et al., 2011).

$$SWt = SWo + \sum_{t=1}^{t}(R - Qsurf - ET - Wseep - Qgw) \quad (1)$$

where *SWt* is the last water amount in the soil (mm), *SWo* is the early soil water amount (mm), *t* is time (days), *R* is the precipitation amount (mm), *Qsurf* is the surface runoff (mm), *ET* is evapotranspiration (mm), *Wseep* is the deep infiltration (mm), and *Qgw* is the amount of flow return (mm).

The methodology of the SWAT model comprises four distinct phases: watershed delineation, HRU development, climatic data input, and execution of the SWAT model. The SWAT model utilizes the DEM to represent the topography of the study watershed. LULC, soil, and weather data imitate and simulate hydrological processes (Ware et al., 2023).

The Cisadane watershed boundaries was delineated using a DEM, allowing for an examination of the drainage patterns of the land surfaces. The HRUs of the study watershed were created by spatially overlaying a land-use map with seven classes, a slope map with five classes, and a soil map with six classes through a threshold of 0%. Daily climate data, including rainfall, maximum and minimum temperature, humidity, wind, and sunshine hours, for 2021 from two stations were input into the model.

The SWAT simulation process can be divided into preparation and processing. During the preparation stage, the flow and direction of water through the landscape were calculated to delineate the watershed. HRU overlays were used to classify land cover and soil types according to SWAT standards. Weather data from gauges were collected and inputted into the model. In the processing stage, the SWAT model was used to calculate various outputs such as streamflow, groundwater flow, direct runoff, water yield, sedimentation, and contaminants. This study primarily focuses on surface runoff, lateral flow, groundwater recharge, water yield, and the evapotranspiration of the watershed (**Figure 2**). These outputs were then analyzed to understand the overall water cycle and potential impacts on the environment.

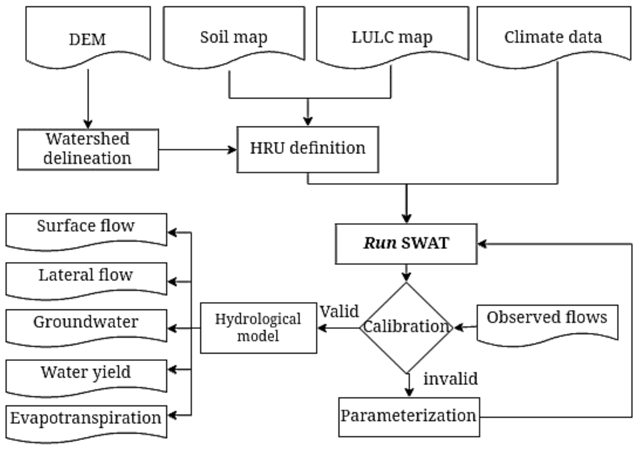

Figure 2. Stages of SWAT analysis in the Cisadane watershed.

Model calibration involves adjusting the model parameters within the recommended ranges to optimize the simulated output to match the observed data. The model contains a series of calibration parameters that can modify these components to represent site-specific watershed conditions (Neitsch et al., 2011). Calibration was performed using the SUFI-2 algorithm to optimize key parameters, such as CN2, ALPHA_BF, and GW_DELAY. Model validation is conducted to determine the model output's accuracy level. The SWAT model was calibrated using observed streamflow data water post Serpong from 2017–2020 and validated with data from 2021. The validation done by performing discharge estimation simulations using a model that has been calibrated. The model's validity is based on the appearance of the relationship between the discharge model and actual discharge graphically, and statistical test results with different objective functions. Statistical parameters, including the Nash–Sutcliffe efficiency (NSE) and determination coefficient (R^2) were used for the study, as outlined in Equations (2) and (3), respectively (Moriasi et al., 2007). Evaluation metrics are used to assess the accuracy of the model output.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i} - Q_{mobs})^2} \quad (2)$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}(Q_{obs,i} - Q_{mobs}) \times (Q_{sim,i} - Q_{msim})\right]^2}{\sum_{i=1}^{n}(Q_{obs,i} - Q_{mobs})^2 \times \sum_{i=1}^{n}(Q_{sim,i} - Q_{msim})^2} \quad (3)$$

where $Q_{obs,i}$ is the measured value, $Q_{sim,i}$ is the simulated value, Q_{mobs} is the mean observed value, and Q_{msim} is the mean simulated value.

Simulations are run by including different scenarios of LULC in the years analyzed (2030 and 2050). The three scenarios are business as usual (BAU), protecting paddy fields (PPF), and protecting forest areas (PFA). Integration of a Markov chain and a cellular automata model (CA–Markov) with multiple-criteria evaluation (MCE) was used to project land-use changes in the watershed for the future period (Ambarwulan et al., 2023). The output results are then used to evaluate the impact of changes in land cover on the response hydrology so that the ideal scenario can be obtained.

3. Data analysis and results

3.1. Hydrological model

The land units in the Cisadane watershed consist of six groups (**Figure 3**). The land unit with the most significant area is Cambisol, with an area of 51,693.40 ha (34,1%), while the lowest area in Regosols was 12,209.63 ha (8%). Cambisols are a soil group without a layer of accumulated clay, humus, or iron and aluminum oxides. They are usually suitable for agriculture due to their favourable structure and high mineral content limited by terrain and climate (Khresat, 2005). Regosol soil has low soil fertility and water availability because of low water-holding ability or water retention.

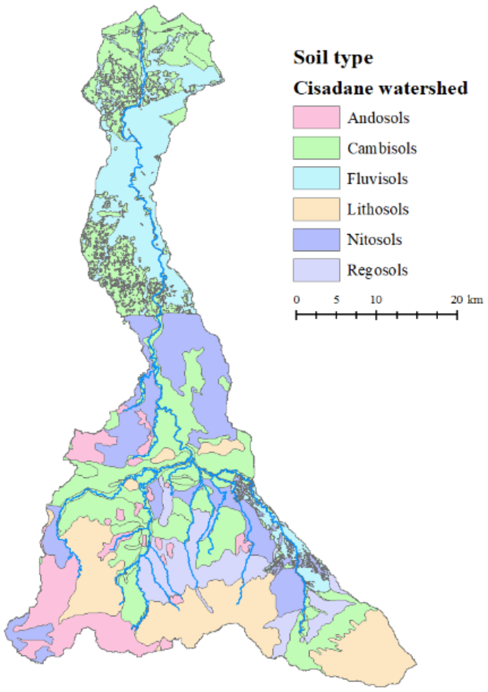

Figure 3. Soil type map of the Cisadane watershed.

In the SWAT model, the hydrologic soil group (HSG) is a vital factor that impacts the rainfall-runoff process. The HSG classification system categorises land based on its hydrological characteristics. It ranges from well-drained soils (HSG type A) to poorly drained soils (HSG type D) (Yang et al., 2018). The majority of soils in this watershed belong to the Group C category, which has soil attributes with moderately high runoff potential, less than 50% sand, 20%–40% clay, and various loamy textures. The soil structure is dense and less permeable, and the particles are closely packed (Abraham et al., 2019). Only a small fraction of the watershed is designated type D soils, with high runoff potential and more than 40% clay.

The Cisadane watershed has diverse topography, ranging from flat to mountainous terrain, with an altitude range of 0 to 2590 m above sea level (**Figure 4**). DEM data processing with a 30-m resolution has classified the land slope into five classes based on (BPDASPS, 2013), with the dominant slope being 0%–8%, covering an area of 60,980.4 ha (40.5%). A gentle north slope and a steeper south slope characterize the watershed's topography. Areas with gentle slopes, such as industry, settlements, and other community practices, are generally suitable for economic growth. On the other hand, steeper slopes over 40% dominant in the north, including Mount Gede, play a crucial role as conservation areas. The slope is a factor that affects the flow characteristics of water because it can determine the size and run-off volume velocity (Garg et al., 2013; Yustika et al., 2016). On gentle slopes, the flow pattern is spread more evenly over the ground surface, forming a broader and more fragmented flow. The steeper the slope, the faster the flow.

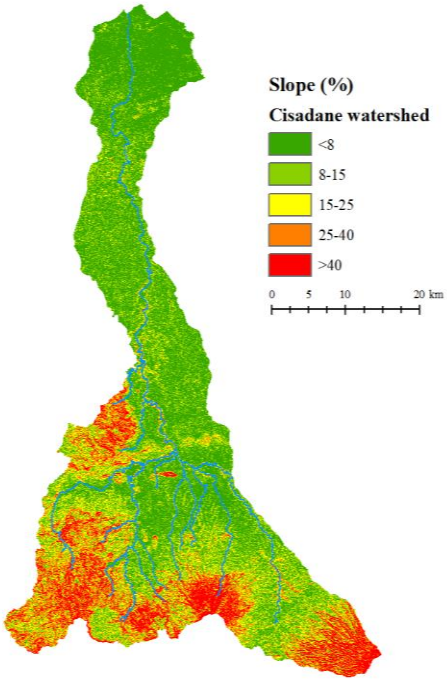

Figure 4. Map of the slope of the Cisadane watershed.

The Cisadane watershed covers an extensive area of land measuring 151,126 hectares. To better manage this large region, the delineation process has divided the catchment area into various sub-basins or catchment areas (Neitsch et al., 2004). It has been divided into 85 sub-basins based on surface elevation to better manage this large area (**Figure 5**). These sub-basins have been divided into 3453 HRUs based on soil type, land use, and slope length. Each HRU is responsible for generating specific hydrological features consistent with its unique characteristics. Breaking down the watershed into smaller units like sub-basins and HRUs, makes it easier to monitor and manage the area's water resources.

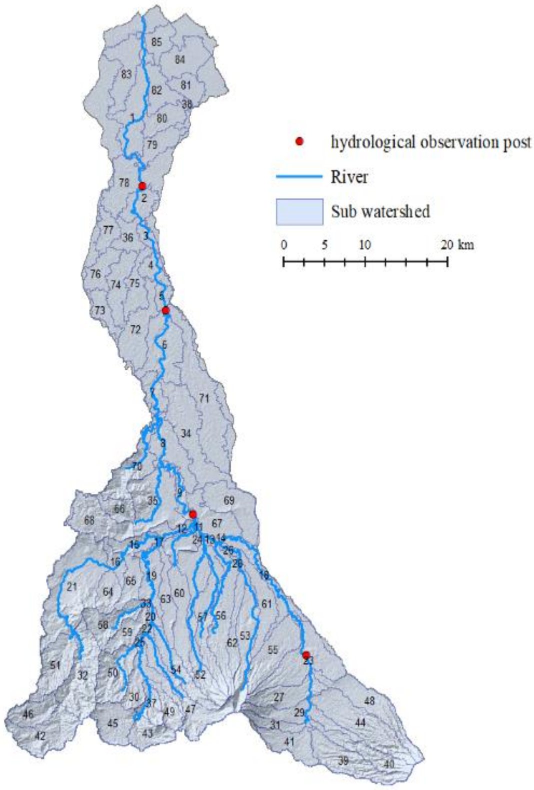

Figure 5. Cisadane watershed delineation map.

Water balance knowledge is crucial in understanding the water cycle, particularly in determining how much water enters (inflow) and leaves (outflow) a particular structure, such as a watershed. Precipitation is a significant inflow component in the water balance of watersheds (Ghalib et al., 2022). The Cisadane watershed area has a tropical climate influenced by the monsoon winds and has two seasons, namely the rainy and dry season. The rainy season in the Cisadane watershed lasts from November to April, while the dry season lasts from June to October (Junaidi, 2013). The peak rainy season happens in January or February, affecting the discharge in the watershed, with the Qmax measuring 12.30 m^3/s. On the other hand, the dry season, which occurs in June, experiences a decrease in precipitation, with the Qmin measuring 5.50 m^3/s (**Figure 6**). This shows that precipitation significantly affects the river's flow in terms of increase and decrease.

The water balance in the Cisadane Watershed is crucial in meeting the area's water needs. If the regional rainfall and surface water runoff in rivers remain high while water usage levels remain normal, the Cisadane Watershed will have a surplus water balance and meet the area's water needs. However, the increased intensity of land-use change can significantly impact the hydrological conditions of inflow and outflow. Therefore, it is essential to maintain a balance between land-use activities and water resources to ensure that the water balance in the watershed remains stable.

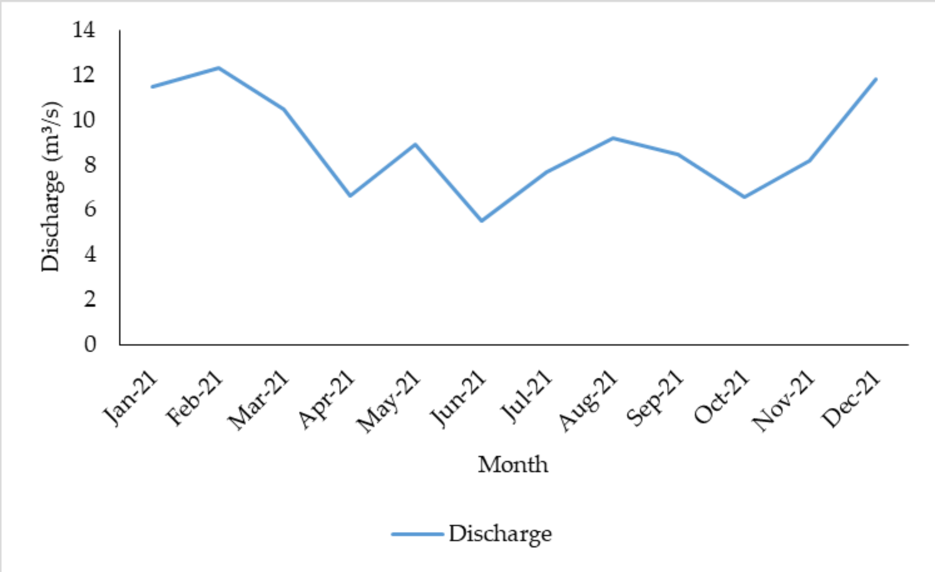

Figure 6. Discharge fluctuation of the Cisadane watershed in 2021.

3.2. SWAT calibration and validation

The SWAT is evaluated by calibration and validation performance by comparing observed and simulated streamflow discharge (**Figure 7**). The calibration process involves adjusting the parameters of the hydrological model to match the observation data. After calibration, the validation process follows, which involves testing the performance of the calibrated hydrological model using independent data not used during calibration.

Statistical approaches such as the R^2 and NSE are utilized to assess the model's performance. The R^2 represents the degree to which the model explains changes in the measured data. The size of the linear relationship between the simulated and experimental standard was the determining factor. The R^2 ranges from 0 to 1. If the value is closer to 1, the independent variable provides almost all the necessary information to forecast the dependent variable (Moriasi et al., 2015). In contrast to the variance in observed data, the NSE evaluates the normalized relative amount of remaining variation. The NSE ranges from 1.0 to $-\infty$, with 1.0 representing the best fit (Mekonnen and Manderso, 2023).

The model's performance is considered satisfactory if the NSE value is greater than 0.75, satisfactory between 0.36 and 0.75, and inadequate if below 0.36 (Moriasi et al., 2007). Based on the calibrated simulation results, the R^2 value is 0.52, and the NS is 0.51, indicating acceptable model performance. The calibration improved model performance with a previously lower R^2 of 0.39 and NS of 0.27. Validation results showed satisfactory model performance with an R^2 value of 0.51 and an NS value of 0.49. Hence, this model can predict future hydrological responses in the Cisadane watershed.

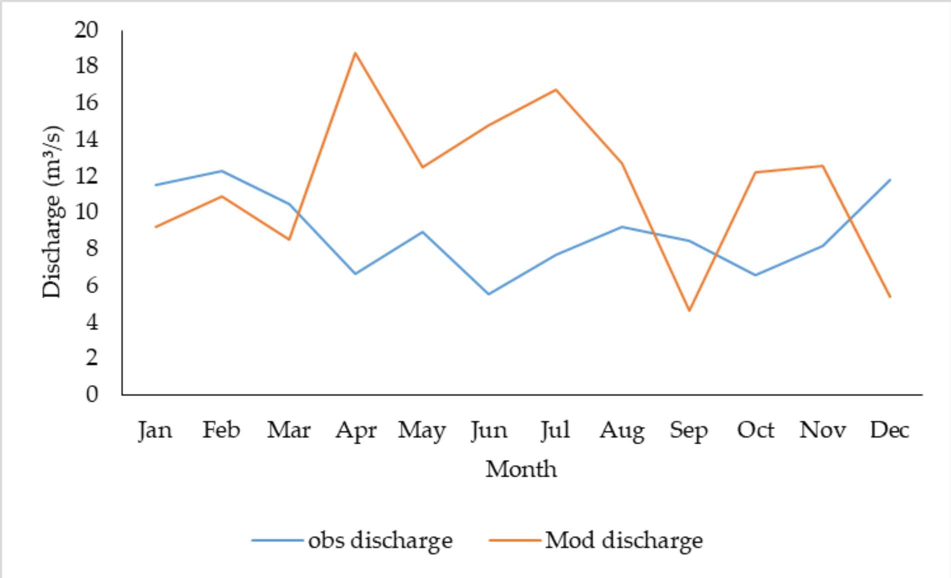

Figure 7. Modelled and observed hydrographs after calibration (m^3/sec) in 2021.

3.3. Scenario of land use/cover change on hydrological characteristics

The three scenarios were simulated using the same rainfall input, 2764.2 mm/year. Rainfall will be partitioned into several hydrological processes, including evapotranspiration, runoff, and changes in land flow due to changes in land cover. The BAU scenario projects future conditions assuming no interventions are implemented to control land-use change in the Cisadane watershed, such as urban expansion and deforestation for agriculture. The scenario incorporates an annual population growth rate of approximately 1.2% (BPS, 2024), influenced by ongoing urbanization and migration trends. This growth intensifies demands for land and resources, exacerbating land-use pressures. Economic development patterns are presumed to persist along historical trends, with limited emphasis on sustainable practices. The scenario excludes considerations of technological advancements, climate adaptation strategies, or stricter environmental regulations, making it a baseline to evaluate the potential impacts of intervention strategies. By highlighting unregulated outcomes, the BAU scenario emphasizes the urgency of sustainable planning and policy reforms.

Under this scenario in 2050, the watershed will be predominantly built up, followed by dryland farms, forests, paddy fields, plantations, and waterbodies (Ambarwulan et al., 2023). Compared to the year 2030, there has been a decrease in the forest area, paddy fields, and dryland farms, while built-up areas have increased. The built-up area increase is particularly significant in the downstream and midstream areas. Previously existing paddy fields and dryland farms are expected to be converted into impervious areas. Meanwhile, in the upstream area, the forest area is expected to be mainly converted into plantation. These changes are expected to significantly impact the environment and ecosystem of the study catchment area.

Table 2. Values and changes in annual hydrological components in the BAU scenario.

Parameter	Year LULC		
	2030 (mm)	**2050 (mm)**	**Difference (mm)**
Surface flow	486.5	642.5	156.0
Lateral flow	140.5	220.6	80.1
Groundwater	680.8	610.6	−70.2
Water yield	1870.5	1620.4	−250.1
Evapotranspiration	650.4	430.6	−219.8

Implementing the BAU scenario in 2030–2050 increases surface flow by 156 mm due to the increasingly limited catchment areas. Another increase in hydrological response occurred in lateral flow, namely 80.1 mm (**Table 2**). This scenario reduces groundwater flow, water yield, and evapotranspiration by 70.2 mm, 250.1 mm, and 219.8 mm. As suggested by the BAU scenario, a massive land-use conversion from vegetated areas into built-up areas, will significantly reduce canopy interception and soil infiltration capacity, transforming a significant fraction of rainfall into surface run-off (Marhaento et al., 2018). These findings highlight the urgent need to integrate green infrastructure into development plans, such as permeable pavements and urban green spaces. Moreover, the changes in groundwater recharge suggest potential long-term impacts on water availability, which should be considered in future watershed management strategies.

Under scenario PPF in 2050, the watershed is predominantly built up, followed by dryland farms, paddy fields, forests, plantations, and waterbodies. Compared to 2030, built-up, paddy fields and plantations increased while dryland farms and forests decreased. This scenario comes from the fact that it supports the food security function for each region in Indonesia (Ambarwulan et al., 2023). Besides supporting food security, rice fields will contribute significantly to a country’s economy. The increase in the coverage of paddy fields in the PPF scenario is a positive sign, but it also highlights the need for sustainable farming practices.

The current condition of the watershed ecosystem based on the PPF scenario is similar to the results of the BAU scenario. In this scenario, there is a slight increase in surface and lateral flow of 148 mm and 76.5 mm, less than that observed in the BAU scenario. However, there is a decrease in groundwater, water yield, and evapotranspiration of 68 mm, 220 mm, and 185.5 mm (**Table 3**). The analysis of changes between 2030 and 2050 indicates an insignificant variation, reflecting only a slight improvement in watershed conditions over time. This improvement can be attributed to the adoption of sustainable agricultural practices, which significantly affect watershed management. These practices help maintain the ecological integrity of rice field ecosystems, optimize water use efficiency, and mitigate soil erosion. Additionally, they play a critical role in reducing flooding and drought risk while sustaining soil fertility.

Table 3. Values and changes in annual hydrological components in the PPF scenario.

Parameter	Year LULC		
	2030 (mm)	**2050 (mm)**	**Difference (mm)**
Surface flow	485.5	633.5	148.0
Lateral flow	138.5	215.0	76.5
Groundwater	670.8	602.8	−68.0
Water yield	1820.5	1600.5	−220.0
Evapotranspiration	652.3	466.8	−185.5

Such findings underscore the importance of promoting sustainable land-use practices in agricultural areas to ensure long-term ecosystem stability and resilience against hydrological challenges. By implementing these practices, watershed management strategies can effectively balance environmental conservation with agricultural productivity.

Based on the PFA scenario projection for the year 2050, the majority of the watershed is expected to be predominantly occupied by built-up areas, followed by forests, dryland farms, plantations, paddy fields, and water bodies. However, compared to 2030, a few noteworthy changes have been observed in the land-use pattern. There has been an increase in the area covered by forests, built-up areas, and plantations, while the area occupied by dryland farms and paddy fields has decreased. The PFA scenario prioritizes the conservation and expansion of forest areas, which has increased forest cover. The expansion of built-up areas and plantations can be attributed to the growth in population and the need for resources. At the same time, the decrease in dryland farms and paddy fields may be due to changes in agricultural practices and land-use policies. The PFA scenario aims to balance development and conservation within the Cisadane watershed by promoting sustainable land use practices. It focuses on preserving critical resources like forests and waterways to support biodiversity and ecosystem services while ensuring the watershed's resilience for future generations. By integrating conservation with development planning and fostering stakeholder collaboration, the scenario aims to harmonize economic growth and environmental stewardship, mitigating risks to water quality, biodiversity, and community livelihoods to benefit present and future generations.

The PFA scenario projects changes in the hydrological response from 2030 to 2050. Surface and lateral flow will increase by 139 mm and 74.6 mm, respectively, and then groundwater, water yield, and evapotranspiration will decrease by 66 mm, 208.5 mm, and 170.5 mm (**Table 4**). Notably, the magnitudes of these changes are smaller compared to the two previous scenarios.

Table 4. Values and changes in annual hydrological components in the PFA scenario.

Parameter	Year LULC		
	2030 (mm)	**2050 (mm)**	**Difference (mm)**
Surface flow	484.5	623.5	139.0
Lateral flow	128.5	203.1	74.6
Groundwater	658.8	592.8	−66.0
Water yield	1880.5	1672.0	−208.5
Evapotranspiration	666.4	495.9	−170.5

This reduction in hydrological impacts can be attributed to expanding green areas, particularly forests, due to protected forest conservation, sustainable forest management, and initiatives to control deforestation and forest degradation. These measures enhance the ability of the ecosystem to regulate water flow, reduce surface runoff, and maintain water infiltration, thereby improving overall watershed health.

The findings highlight the critical role of forest conservation and sustainable land-use practices in mitigating adverse hydrological impacts. By increasing green cover, such practices reduce the intensity of surface and lateral flow and contribute to better groundwater recharge and evapotranspiration regulation. These improvements emphasize the importance of integrated watershed management prioritizing ecological conservation to ensure long-term sustainability and resilience to hydrological changes.

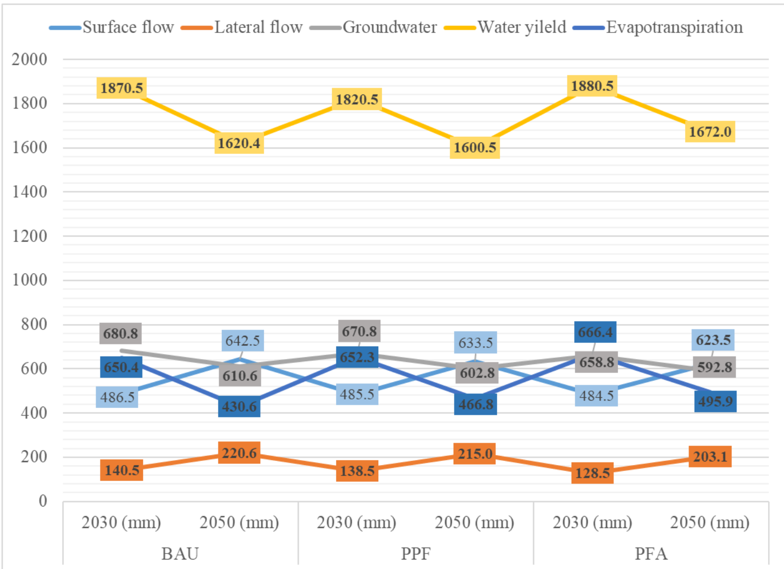

Figure 8. Values and changes of annual hydrological components in the scenarios.

Figure 8 showcases the changes in annual hydrological components between 2030 and 2050. The comparison showed that the PFA scenario had the lowest surface flow in both study years, with values of 484.5 mm and 623.5 mm, respectively. Conversely, the BAU scenario had the highest surface flow, with figures of 486.5 mm and 642.5 mm in 2030 and 2050. Similar patterns were observed for lateral flow components, with the BAU scenario having the highest values of 140.5 mm and 220.6 mm. In comparison, the lowest values were recorded in the PFA scenario at 128.5 mm and 203.1 mm. Groundwater levels were highest in the BAU scenario, at 680.8 mm and 610.6 mm, and lowest in the PFA scenario, with values of 658.8 mm and 592.8 mm. The PPF scenario showed the lowest water yield conditions, with 1820.5 mm and 1600.5 mm values, whereas the PFA scenario exhibited the highest water yield, with 1880.5 mm and 1672.0 mm. These findings provide valuable insights into the impacts of different scenarios on hydrological components, which can be useful for water resource management and planning in the Cisadane watershed.

4. Discussion

This study highlights the significant impacts of land use and cover changes, such as deforestation, urbanization, and agricultural expansion on the Cisadane watershed's hydrological balance. Using the SWAT model, the research evaluated BAU, PPF, and PFA scenarios. The BAU scenario is marked by reduced forests and paddy fields, increased surface runoff and diminished water absorption capacity, exacerbating flooding risks and reducing water availability (Utami et al., 2020). Conversely, the PFA scenario demonstrated improved outcomes by enhancing water infiltration and regulating runoff.

Several studies have compared scenarios such as urban expansion, agricultural intensification, or forest conservation have provided insights into their effectiveness in influencing hydrological parameters (Elfert and Bormann, 2010; Marhaento et al., 2018; Tankpa et al., 2021; Zhang et al., 2016). Under the BAU scenario, the Cisadane watershed experiences the highest increase in the mean annual surface flow and lateral flow. The findings align with similar studies in tropical watersheds, such as the Citarum basin, where urbanization also led to increased runoff and reduced groundwater recharge. Land conversion in the upstream areas of the Cisadane watershed will significantly reduce canopy interception and soil infiltration capacity and diminish the watershed's capacity to retain or absorb rainwater. As a result, most of the rainwater transforms into surface runoff (Marhaento et al., 2017) and flows rapidly to the downstream part of the watershed (Nilda et al., 2015). This scenario also witnesses a significant decrease in evapotranspiration, reducing water yield due to increased surface runoff and diminished infiltration. Compare to the previous study in East African Rift Valley, groundwater flow increased due to urbanization (Yifru et al., 2021). The directions of change in the water balance components by land-use change in this study align with other studies such as Northwest Ethiopia and Texas (Kim et al., 2016; Tewabe and Fentahun, 2020).

The PPF scenario shows intermediate surface runoff, lateral flow, groundwater, water yield, and evapotranspiration changes during the years 2030–2050. The agricultural areas tend to produce more runoff due to compaction of lower soil horizons during land tilling (Githui et al., 2009). It depends on the extent of land conversion and vegetation cover. However, the scenario demonstrates a better quantity of hydrological responses than BAU, as it promotes higher vegetation cover, transpiration rate, and water retention capacity.

The PFA scenario significantly improves hydrological responses in this watershed. This finding is supported by the fact that the lowest amount of surface and lateral flow during 2030–2050 was found in the PFA scenario. Forests can absorb more water through the roots, slow down water flow, and reduce horizontal water flow below the surface. Previous studies in Kenya, Philippines and China have also confirmed that forest expansion enhances infiltration rates, and decreases surface runoff (Briones et al., 2016; Githui et al., 2009; Li et al., 2015). The PFA scenario achieves the highest water yield by enhancing soil moisture retention, groundwater recharge, and water availability within the watershed. However, it also results in the lowest groundwater value due to higher evapotranspiration rates of forest vegetation (Huang et al., 2016; Puno et al., 2019; Tarigan et al., 2018). Due to the extensive leaf area index and long growth season, forests tend to have higher ET than other land cover types (Yang et al., 2015). It exhibits the highest evapotranspiration rates, which promotes transpiration, interception, and soil evaporation thereby maintaining ecological balance and hydrological integrity.

Vegetation, particularly forests, plays a crucial role in regulating hydrological processes by intercepting rainfall, reducing surface runoff (Larbi et al., 2020), and enhancing infiltration by improving soil structure and increasing soil moisture retention (Guevara-Escobar et al., 2007). Conversely, urbanization disrupts natural landscapes, replacing permeable surfaces with impervious ones, disrupting the water cycle (Yang et al., 2018) and increasing flood risk and drought. Those risks can potentially be reduced by introducing and enforcing land-use planning regulations. Integrated watershed management approaches recognize the interconnectedness of land use planning, water resource management, and environmental conservation. Considering holistically socio-economic, ecological, and hydrological factors is crucial for promoting sustainable development and resilience in watersheds.

In order to effectively understand and mitigate the effects of changes in land use and land cover on hydrological responses in watersheds, it is essential for future research and management efforts to address some key challenges such as data scarcity, model uncertainty, rapid urbanization, stakeholder misalignment, and climate change impacts. The integration of advanced modelling techniques, real-time data, and stakeholder engagement strategies are among the opportunities for improvement. It will improve predictive capabilities, inform decision-making, and enhance the sustainability of water resources and ecosystems in the face of ongoing environmental change.

5. Conclusions

This study uses the SWAT model to simulate the hydrological responses to land cover change scenarios in The Cisadane watershed. An analysis of the variation in discharge in the Cisadane watershed in 2021 reveals significant differences. The study's results indicated significant differences in discharge variations, with maximum and minimum discharge values of 12.30 m^3/s and 5.50 m^3/s. The model calibration achieved satisfactory performance, with R^2 and NSE values of 0.52 and 0.51, respectively, and validation against the observed streamflow data yielded acceptable statistical results of R^2 = 0.51 and NSE = 0.49. The study revealed that intensified land-use changes significantly impacted hydrological conditions, affecting, affecting various factors such as surface runoff, lateral flow, groundwater flow, water yield, and evapotranspiration. The BAU scenario showed rapid land conversion to built-up areas, which increased surface runoff, lateral flow, and groundwater flow while reducing evapotranspiration and water yield due to decreased infiltration rates on impervious surfaces. On the other hand, the PFA scenario, which involved expanding forest areas, emerged as the most favourable for watershed management, positively affecting the ecosystem. The expansion of green vegetation in the PFA scenario potentially enhanced water absorption. These findings underscored the importance of land-use planning in mitigating water-related risks and maintaining ecological balance in the Cisadane watershed. By providing science-based information, local decision-makers and stakeholders can implement site-specific control measures and strategies for achieving water balance and sustainable development within watersheds.

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References

[BPDASPS] Direktur Jenderal Bina Pengelolaan Daerah Aliran Sungai dan Perhutanan Sosial. Peraturan Direktur Jenderal Bina Pengelolaan Daerah Aliran Sungai dan Perhutanan Sosial tentang Pedoman Identifikasi Karakteristik Daerah Aliran Sungai, Nomor: P. 3/V-SET/2013. Jakarta: 2013.

[BPS] Badan Pusat Statistik . Average Population Growth by Province, 1971–2024. Https://WwwBpsGoId/Id/Statistics-Table/1/MTI2OCMx/Average-Population-Growth-by-Province--1971---2024Html 2024.

[KLHK] Kementerian Lingkungan Hidup dan Kehutanan. Rencana Strategis Direktorat Jenderal Pengendalian Daerah Aliran Sungai dan Hutan Lindung 2015 – 2019. Jakarta: 2015.

Abraham S, Huynh C, Vu H. Classification of soils into hydrologic groups using machine learning. Data (Base) 2019;5:2. https://doi.org/10.3390/data5010002.

Ambarwulan W, Yulianto F, Widiatmaka W, Rahadiati A, Tarigan SD, Firmansyah I, et al. Modeling land use/land cover projection using different scenarios in the Cisadane Watershed, Indonesia: Implication on deforestation and food security. The Egyptian Journal of Remote Sensing and Space Science 2023;26:273–83. https://doi.org/10.1016/j.ejrs.2023.04.002.

Arnold JG, Srinivasan R, Muttiah RS, Williams JR. Large area hydrologic modeling and assessment part1: Model development. J Am Water Resour Assoc 1998;34:73–89. https://doi.org/10.1111/j.1752-1688.1998.tb05961.x.

Bagstad KJ, Semmens DJ, Waage S, Winthrop R. A comparative assessment of decision-support tools for ecosystem services quantification and valuation. Ecosyst Serv 2013;5:27–39. https://doi.org/10.1016/j.ecoser.2013.07.004.

Balist J, Malekmohammadi B, Jafari HR, Nohegar A, Geneetti D. Detecting land use and climate impacts on water yield ecosystem service in arid and semi-arid areas. A study in Sirvan River Basin-Iran. Appl Water Sci 2022;12:4. https://doi.org/10.1007/s13201-021-01545-8.

Briones R, Ela V, Bantayan N. Hydrologic Impact Evaluation of Land Use and Land Cover Change in Palico Watershed, Batangas, Philippines Using the SWAT Model. Journal of Environmental Science and Management 2016;19:96–107. https://doi.org/10.47125/jesam/2016_1/10.

Cao Z, Wang S, Luo P, Xie D, Zhu W. Watershed Ecohydrological Processes in a Changing Environment: Opportunities and Challenges. Water (Base) 2022;14:1502. https://doi.org/10.3390/w14091502.

Carlotto T, Klaus J, Chaffe PLB. An open-source GIS preprocessing tool for the ParFlow hydrological model (PFGIS-Tool v1.0.0). Environmental Modeling & Software 2023;169:105824. https://doi.org/10.1016/j.envsoft.2023.105824.

Castro C V., Maidment DR. GIS preprocessing for rapid initialization of HEC-HMS hydrological basin models using web-based data services. Environmental Modeling & Software 2020;130:104732. https://doi.org/10.1016/j.envsoft.2020.104732.

de Groot RS, Wilson MA, Boumans RMJ. A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecological Economics 2002;41:393–408. https://doi.org/10.1016/S0921-8009(02)00089-7.

Elfert S, Bormann H. Simulated impact of past and possible future land use changes on the hydrological response of the Northern German lowland 'Hunte' catchment. J Hydrol (Amst) 2010;383:245–55. https://doi.org/10.1016/j.jhydrol.2009.12.040.

Endang T, Tessie K. Evaluasi Perubahan Penggunaan Lahan Kecamatan di Daerah Aliran Sungai Cisadane Kabupaten Bogor. Jurnal Wilayah Dan Lingkungan 2014;2:55. https://doi.org/10.14710/jwl.2.1.55-72.

Francesconi W, Srinivasan R, Pérez-Miñana E, Willcock SP, Quintero M. Using the Soil and Water Assessment Tool (SWAT) to model ecosystem services: A systematic review. J Hydrol (Amst) 2016;535:625–36. https://doi.org/10.1016/j.jhydrol.2016.01.034.

Garg V, Nikam BR, Thakur PK, Aggarwal SP. Assessment of the effect of slope on runoff potential of a watershed using NRCS-CN method. International Journal of Hydrology Science and Technology 2013;3:141. https://doi.org/10.1504/IJHST.2013.057626.

Ghalib W, Majeed M, Al-Taai O. Influence of Precipitation and Evaporation on Water Balance in Iraq 2022.

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 / Estimation des impacts du changement d'occupation du sol sur l'écoulement à l'aide de SWAT: étude du cas du bassin de Nzoia, Kenya. Hydrological Sciences Journal 2009;54:899–908. https://doi.org/10.1623/hysj.54.5.899.

Guevara-Escobar A, Gonzalez-Sosa E, Ramos-Salinas M, Hernandez-Degado GD. Experimental analysis of drainage and water storage of litter layers. Hydrol Earth Syst Sci 2007;11:1703–16. https://doi.org/10.5194/hess-11-1703-2007.

Gumelar AR, Alamsyah AT, Gupta IBH, Syahdanul D, Tampi DM. Sustainable Watersheds: Assessing the Source and Load of Cisadane River Pollution. International Journal of Environmental Science and Development 2017;8:484–8. https://doi.org/10.18178/ijesd.2017.8.7.1001.

Huang X-D, Shi Z-H, Fang N-F, Li X. Influences of land use change on baseflow in mountainous watersheds. Forests 2016;7:16. https://doi.org/10.3390/f7010016.

Junaidi E. Peranan penerapan agroforestry terhadap hasil air Daerah Aliran Sungai (DAS) Cisadane. Jurnal Penelitian Agroforestry 2013;1:41–53.

Kaliraj S, Chandrasekar N, Ramachandran KK, Lalitha M. GIS based NRCS-CN modeling of rainfall-runoff in river Thamirabarani sub-basin, Southern India. Journal of Hydro-Environment Research 2023;49:10–27. https://doi.org/10.1016/j.jher.2023.07.001.

Kayitesi NM, Guzha AC, Mariethoz G. Impacts of land use land cover change and climate change on river hydro-morphology- a review of research studies in tropical regions. J Hydrol (Amst) 2022;615:128702. https://doi.org/10.1016/j.jhydrol.2022.128702.

Khresat S. Formation and properties of Inceptisols (Cambisols) of major agricultural rainfed areas in Jordan. Arch Agron Soil Sci 2005;51:15–23. https://doi.org/10.1080/03650340400026545.

Kim HW, Li M-H, Kim J-H, Jaber F. Examining the Impact of Suburbanization on Surface Runoff using the SWAT. Int J Environ Res 2016;10:379–90. https://doi.org/10.22059/ijer.2016.58757.

Larbi I, Obuobie E, Verhoef A, Julich S, Feger K-H, Bossa AY, et al. Water balance components estimation under scenarios of land cover change in the Vea catchment, West Africa. Hydrological Sciences Journal 2020;65:2196–209. https://doi.org/10.1080/02626667.2020.1802467.

Li Z, Deng X, Wu F, Hasan S. Scenario analysis for water resources in response to land use change in the middle and upper reaches of the Heihe River Basin. Sustainability 2015;7:3086–108. https://doi.org/10.3390/su7033086.

Luo Y, Yang Y, Yang D, Zhang S. Quantifying the impact of vegetation changes on global terrestrial runoff using the Budyko framework. J Hydrol (Amst) 2020;590:125389. https://doi.org/10.1016/j.jhydrol.2020.125389.

Marhaento H, Booij MJ, Hoekstra AY. Hydrological response to future land-use change and climate change in a tropical catchment. Hydrological Sciences Journal 2018;63:1368–85. https://doi.org/10.1080/02626667.2018.1511054.

Marhaento H, Booij MJ, Rientjes THM, Hoekstra AY. Attribution of changes in the water balance of a tropical catchment to land use change using the SWAT model. Hydrol Process 2017;31:2029–40. https://doi.org/10.1002/hyp.11167.

Maru H, Haileslassie A, Zeeke T, Teferi E. Analysis of the impacts of land use land cover change on streamflow and surface water availability in Awash Basin, Ethiopia. Geomatics, Natural Hazards and Risk 2023;14:1–25. https://doi.org/10.1080/19475705.2022.2163193.

Mekonnen YA, Manderso TM. Land use/land cover change impact on streamflow using Arc-SWAT model, in case of Fetam watershed, Abbay Basin, Ethiopia. Appl Water Sci 2023;13:111. https://doi.org/10.1007/s13201-023-01914-5.

Memarian H, Balasundram SK, Abbaspour KC, Talib JB, Boon Sung CT, Sood AM. SWAT-based hydrological modeling of tropical land-use scenarios. Hydrological Sciences Journal 2014;59:1808–29. https://doi.org/10.1080/02626667.2014.892598.

Moriasi D, Anaba LA, Banadda N, Kiggundu N, Wanyama J, Enge B. Hydrologic and Water Quality Models: Key Calibration and Validation Topics. Trans ASABE 2015;58:1609–18. https://doi.org/10.13031/trans.58.11075.

Moriasi D, J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harme, T. L. Veith. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. Trans ASABE 2007;50:885–900. https://doi.org/10.13031/2013.23153.

Neitsch S, Arnold J, Kiniry J, Williams J. Soil and Water Assessment Tool Theoretical Documentation Version 2009. Texas (US): Texas Water Resources Institute; 2011.

Neitsch SL, Armold JG, Kiniry JR, Srinivasan R, William JR. Soil and Water Assessment Tools Input/Output File Documentation Version 2005. Texas: Agricultural Research Service (US); 2004.

Nilda N, Adnyana IWS, Merit IN. Analisis Perubahan Penggunaan Lahan dan Dampaknya terhadap Hasil Air di DAS Cisadane Hulu. ECOTROPHIC : Jurnal Ilmu Lingkungan (Journal of Environmental Science) 2015;9:35. https://doi.org/10.24843/EJES.2015.v09.i01.p05.

Pontes PRM, Fan FM, Fleischmann AS, de Paiva RCD, Buarque DC, Siqueira VA, et al. MGB-IPH model for hydrological and hydraulic simulation of large floodplain river systems coupled with open source GIS. Environmental Modeling & Software 2017;94:1–20. https://doi.org/10.1016/j.envsoft.2017.03.029.

Puno RCC, Puno GR, Talisay BAM. Hydrologic responses of watershed assessment to land cover and climate change using soil and water assessment tool model. Global Journal of Environmental Science and Management 2019;5:71–82. https://doi.org/10.22034/gjesm.2019.01.06.

Putra PB, Agus C, Adi RN, Susanti PD, Indrajaya Y. Land Use Change in Tropical Watersheds: Will It Support Natural Resources Sustainability? Sustainability in Natural Resources Management and Land Planning, Springer; 2021, p. 63–75.

Rodríguez-Morales JA, Barrios-Calderón R de J, Reyes-Reyes J, Torre D de JP la. Hydrological Processes in a Small Research Watershed under Forest Coverage in the Coast of Chiapas, Mexico. Journal of Geoscience and Environment Protection 2023;11:104–14. https://doi.org/10.4236/gep.2023.113007.

Sáez JP, Martínez-España R, Casalí J, Pérez-Sánchez J, Senent-Aparicio J. A comparison of performance of SWAT and machine learning models for predicting sediment load in a forested Basin, Northern Spain. Catena (Amst) 2022;212:105953. https://doi.org/10.1016/j.catena.2021.105953.

Tankpa V, Wang L, Awotwi A, Singh L, Thapa S, Atanga RA, et al. Modeling the effects of historical and future land use/land cover change dynamics on the hydrological response of Ashi watershed, northeastern China. Environ Dev Sustain 2021;23:7883–912. https://doi.org/10.1007/s10668-020-00952-2.

Tarigan S, Wiegand K, Slamet B. Minimum forest cover required for sustainable water flow regulation of a watershed: a case study in Jambi Province, Indonesia. Hydrology and Earth System Sciences 2018; 22(1): 581–594. https://doi.org/10.5194/hess-22-581-2018

Tewabe D, Fentahun T. Assessing land use and land cover change detection using remote sensing in the Lake Tana Basin, Northwest Ethiopia. Cogent Environ Sci 2020;6. https://doi.org/10.1080/23311843.2020.1778998.

Utami W, Wahjunie E, Tarigan S. Karakteristik Hidrologi dan Pengelolaannya dengan Model Hidrologi Soil and Water Assessment Tool Sub DAS Cisadane Hulu. Jurnal Ilmu Pertanian Indonesia 2020;25:342–8. https://doi.org/10.18343/ipi.25.3.342.

Varga M, Balogh S, Csukas B. GIS based generation of dynamic hydrological and land patch simulation models for rural watershed areas. Information Processing in Agriculture 2016;3:1–16. https://doi.org/10.1016/j.inpa.2015.11.001.

Ware HH, Mengistu TD, Yifru BA, Chang SW, Chung I-M. Assessment of Spatiotemporal Groundwater Recharge Distribution Using SWAT-MODFLOW Model and Transient Water Table Fluctuation Method. Water (Base) 2023;15:2112. https://doi.org/10.3390/w15112112.

Yang Q, Almendinger JE, Zhang X, Huang M, Chen X, Leng G, et al. Enhancing SWAT simulation of forest ecosystems for water resource assessment: A case study in the St. Croix River basin. Ecol Eng 2018;120:422–31. https://doi.org/10.1016/j.ecoleng.2018.06.020.

Yang Q, Tian H, Li X, Tao B, Ren W, Chen G, et al. Spatiotemporal patterns of evapotranspiration along the North American east coast as influenced by multiple environmental changes. Ecohydrology 2015;8:714–25. https://doi.org/10.1002/eco.1538.

Yifru BA, Chung I-M, Kim M-G, Chang SW. Assessing the Effect of Land/Use Land Cover and Climate Change on Water Yield and Groundwater Recharge in East African Rift Valley using Integrated Model. J Hydrol Reg Stud 2021;37:100926. https://doi.org/10.1016/j.ejrh.2021.100926.

Yustika RD, Tarigan SD, Sudadi U. Simulasi manajemen lahan di DAS Ciliwung Hulu menggunakan model SWAT. Informatika Pertanian 2016;21:71. https://doi.org/10.21082/ip.v21n2.2012.p71-79.

Zhang L, Nan Z, Yu W, Ge Y. Hydrological Responses to Land-Use Change Scenarios under Constant and Changed Climatic Conditions. Environ Manage 2016;57:412–31. https://doi.org/10.1007/s00267-015-0620-z.