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Original Article

Modeling Future Scenarios for Moiben River Flow Using SWAT and CA-Markov: Implications for Sustainable Watershed Management

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Abstract

This study utilized an integrated Cellular Automata–Markov (CA–Markov) and Soil and Water Assessment Tool (SWAT) modeling approach to forecast the hydrological response of the Moiben River watershed to future land use and climate scenarios for the year 2055, recognizing the river's critical role in regional water supply. The CA–Markov model, informed by historical LULC trends between 2005 and 2021, projected a Business-as-Usual (BAU) scenario characterized by dominant agricultural expansion (covering over 71% of the area) at the expense of crucial Natural Forest and Grassland covers. Subsequently, the SWAT model, calibrated and validated for the watershed and forced by the Representative Concentration Pathway (RCP 6.0) climate scenario, simulated the corresponding changes in river flow. The simulation results revealed a statistically significant destabilization of the river's flow regime (p<0.001) compared to the 2021 baseline, confirming a critical loss of the watershed's natural regulatory capacity. The projected hydrological shifts

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indicate a future defined by extreme variability: severe dry-season flow deficits revealing critically diminished baseflow and groundwater recharge evidenced by declines exceeding 60% in November and 52.91% in December. This scarcity is contrasted by a sharp, short-lived amplification of peak flows (a 52.83% surge in August), indicating a transformation into a flashier system primarily driven by increased surface runoff from the degraded landscape. The study provides quantitative evidence that LULC change is the primary driver of increased flood flashiness and water scarcity, posing significant threats to water security, domestic supply, and ecological health. Consequently, this research validates that proactive, scenario-based hydrological modeling is an indispensable tool for designing adaptive land use governance and conservation policies aimed at mitigating future hydrological stress in the Moiben River watershed.

Keywords: **SWAT, CA-Markov, Land use, River flow modeling, Moiben River, Watershed management**

Introduction

Water resources underpin human welfare, food security, ecosystem health, and economic development across the globe (Jennings et al., 2016; Bitok, Daudi & Arusei, 2025). Rivers, in particular, regulate seasonal flows, supply freshwater for domestic and agricultural uses, recharge vital groundwater stores, transport essential sediments, and support rich biodiversity (Nyingi et al., 2013). Yet, these critical systems face two mounting, interconnected threats: climate change, which alters precipitation patterns and temperature regimes, and land-use and land-cover (LULC) change (including deforestation, agricultural expansion, and urbanization), which profoundly modifies hydrological processes like infiltration, surface runoff, evapotranspiration, and sediment yield (Rongoei et al., 2025; Kerich et al., 2025). To manage watersheds sustainably in the face of these dynamics, researchers must increasingly rely on modeling tools that integrate spatially LULC dynamics with hydrological simulation under future scenarios.

Two of the most widely used and effective modeling tools for this integrated approach are the Cellular Automata–Markov (CA–Markov) model, which excels at projecting future land-use/land-cover transitions based on past trends and driving factors, and the Soil and Water Assessment Tool (SWAT), a physically-based model that rigorously simulates hydrological processes, sediment transport, and water yields under varied spatial and climatic inputs (Arnold et al., 1998; Abbaspour, 2015; Eastman, 2012). Empirical studies around the world consistently demonstrate that combining CA–Markov and SWAT yields superior, policy-relevant insights into how river

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flow regimes are likely to change under alternative futures. For instance, Ji et al. (2021) employed this coupled approach in China's Yellow River Basin to show that projected increases in agricultural and urban land will significantly amplify flood peaks and alter seasonal flows. Similarly, Phan et al. (2020) in Vietnam's Ba River Basin found that combined LULC and climate projections resulted in higher annual runoff and altered baseflow. Other regional studies have confirmed this necessity: Chimdessa et al. (2018) assessed the synergistic effects of land-use and climate change, finding that deforestation and urbanization accelerated surface runoff and increased soil erosion risks, while Li et al. (2020) concluded that ignoring future land-use dynamics in modeling underestimates flood hazards. These studies collectively establish that coupling CA–Markov and SWAT enbles detailed, reliable scenario-based modeling, providing crucial data-driven support for sustainable watershed management at regional and global scales.

In Sub-Saharan Africa, LULCC, coupled with climate variability, continues to exert a significant and challenging influence on watershed hydrology. Across the continent, shifts in land cover from forest to agriculture or settlement are known to substantially alter surface runoff, baseflow, and sediment transport, intensifying water-related hazards and degrading water quality. In Ethiopia, Gashaw et al. (2018) employed CA–Markov and SWAT in the Andassa watershed to project that deforestation-driven land-use change would increase surface runoff while reducing critical groundwater recharge. Schuol et al. (2008) applied SWAT across 17 West African river basins, finding that increasing agricultural land cover significantly influenced the timing and magnitude of river discharge, stressing the need for conservation-based land management. Mustefa Abdule et al. (2023) observed that climate variability compounded by LULC change in eastern Ethiopia resulted in reduced dry-season flow, threatening essential irrigation systems. Tadele et al. (2025) modeled the Weito River catchment, revealing a projected decline in baseflow due to persistent vegetation loss and overgrazing. Encouragingly, Tesfaye et al. (2021) reported that implementing sustainable land-use planning in the Lake Tana sub-basin could successfully mitigate negative hydrological impacts projected for 2050.

The situation is particularly acute in Kenya, where changes in vegetation cover and land management practices have been associated with increased runoff, higher peak flows, sedimentation, and reduced dry-season flows in key basins such as the Nzoia, Mara, and Arror (Kibiiy et al., 2021). Consequently, empirical studies have increasingly combined CA–Markov and SWAT models to simulate river flow dynamics under future scenarios. Githui, Mutua, and Bauwens (2009) applied SWAT to the Nzoia River Basin, showing that deforestation and agricultural expansion increased peak discharge and

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flood frequency. Kamamia et al. (2022) analyzed the Ruiru watershed, concluding that unplanned urban expansion caused increased surface runoff and sediment yield, threatening Nairobi’s water supply. Additional modeling efforts in the Athi and Nairobi River basins have likewise shown that incorporating CA–Markov-predicted land-use transitions into SWAT simulations produces significantly more realistic flow forecasts than using static LULC maps. These national studies underline that future river flow and water security in Kenya are fundamentally dependent on coordinated land-use control, wetland conservation, and urban planning aligned with predictive hydrological modeling insights to achieve true sustainable watershed management.

The Moiben River, a critical sub-basin of the Nzoia watershed located in Uasin Gishu and Elgeyo Marakwet counties, serves as a vital freshwater source for both agricultural and domestic consumption (Rotich et al., 2024). The river originates from the Cherang’any Hills and traverses a diverse and dynamic landscape that includes forested uplands and intensively cultivated lowlands (Akenga et al., 2020). Unfortunately, persistent agricultural expansion, agrochemical use, deforestation, and riparian degradation increasingly threaten the river’s ecological integrity and flow reliability. Water quality studies already report elevated levels of nitrate and phosphate, alongside declining benthic macroinvertebrate diversity in downstream reaches, clearly indicating biological stress (Mutua et al., 2009). These cumulative changes are expected to detrimentally alter hydrological processes, leading to increased surface runoff, reduced infiltration and baseflow, elevated flood risk, and compromised dry-season water supply.

Despite the growing body of research on LULCC and hydrological dynamics in Kenya, methodological gaps persist in integrating land-use forecasting and hydrological simulation for the Moiben watershed. The SWAT model (Arnold et al., 1998; Abbaspour, 2015) has demonstrated strong performance in simulating hydrological responses to land-use and climate variations, while the CA–Markov model (Eastman, 2012) effectively predicts future land-use scenarios based on historical transitions. Combining these models enables scenario-based assessments of potential watershed responses, an approach successfully applied in other Kenyan basins (Olang & Fürst, 2011).

This study addresses this gap by integrating the CA–Markov and SWAT modeling tools to assess the hydrological impacts of projected land use changes and climate scenarios on the Moiben River watershed. Specifically, it seeks to (1) calibrate and validate a SWAT model for current Moiben watershed conditions, (2) simulate future land-use scenarios for 2030 and 2050 using CA–Markov, (3) evaluate river flow responses under combined

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land-use and climate projections, and (4) develop recommendations for sustainable watershed management based on modeled outcomes. Through this integrated modeling approach, the study contributes to advancing evidence-based watershed management and provides a decision-support framework for sustainable land and water resource planning in the Moiben sub-basin and comparable environments.

Materials and Methods

Study Area

The study was conducted in the Moiben River watershed (Figure 1), a vital sub-basin of the Nzoia River system spanning Uasin Gishu and Elgeyo Marakwet counties in western Kenya, located between longitudes 34°50′E–35°37′E and latitudes 0°03′S–0°55′N. Originating from the Cherang'any Hills, the river flows westward through forested uplands and cultivated plains before joining the Nzoia River. The region experiences a tropical highland climate with bimodal rainfall long rains from March to May and short rains from August to October ranging from 900 to 1,400 mm annually, leading to seasonal flow variations from floods to dry-season low flows. Agriculture dominates the local economy, with extensive maize and wheat cultivation alongside smallholder farming of beans, potatoes, and vegetables (Akenga et al., 2020). Expansion of farmland into riparian zones, deforestation and intensive agrochemical use have increased runoff, sedimentation, and pollution. These land use pressures make the Moiben River watershed an ideal setting for modeling future river flow scenarios using integrated CA–Markov and SWAT approaches to guide sustainable watershed management.

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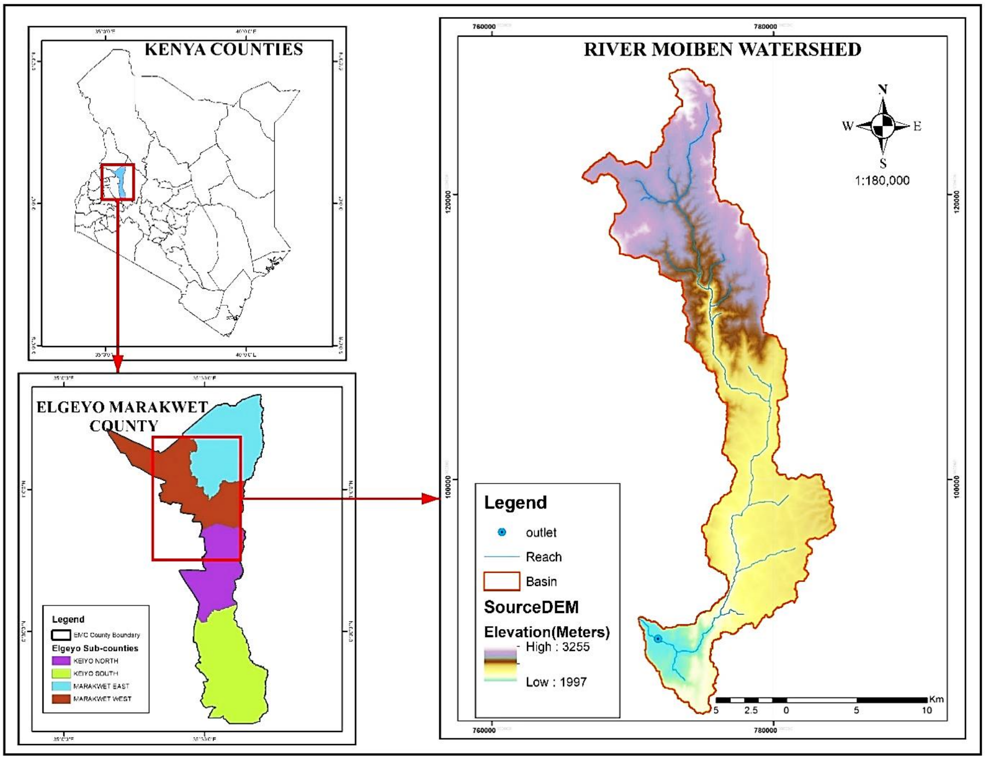

Figure 1: Study area map

LULC Projection Using CA-Markov Land Change Modeler in IDRISI Selva was used to predict 2055 LULC using 2005 and 2021 classified maps. Variables included slope, aspect, elevation, distance to roads, and urban centers.Land change modelers (LCMs) incorporating Markov chain analysis constitute a robust methodology for explaining and forecasting the spatio-temporal transformations of land cover and land use (LULC) patterns. These models leverage on diachronic LULC data, geospatial information and the underlying drivers of change, such as demographic surges or economic fluctuations. This empowers them to predict the probability of LULC transitions (e.g., forest to urban) within a specified time frame in a given area. The Moiben watershed LULC prediction of the year 2055 was generated using the Land Change Modeler (LCM) in the Integrated Decision Support Information System (IDRISI) Selva user interface applying a generalized methodology depicted in Figure 2.

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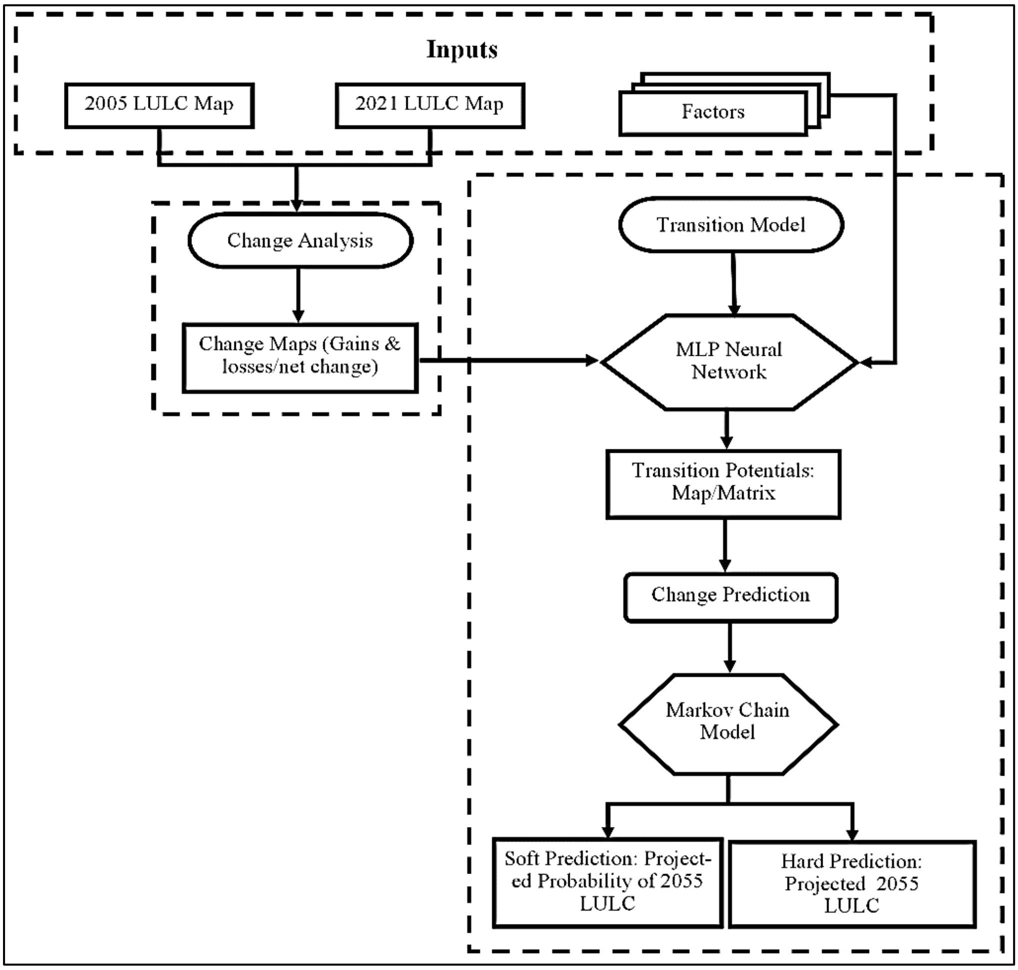

Figure 2: The LCM methodology

The LCM used 2005 and 2021 LULC datasets which had seven identical LULC categories of agriculture, bushland, grassland, natural forest, plantation forest, water and wetland but in different magnitudes (Figure 3). This is a representation of LULC for 2005 and 2021 in IDRISI format, a proprietary file format used by the IDRISI software for storing raster data. It consists of gridded pixel values representing LULC spatial data. The same format stores information about the data’s geographic location, projection and other metadata necessary for proper spatial analysis within the IDRISI software environment.

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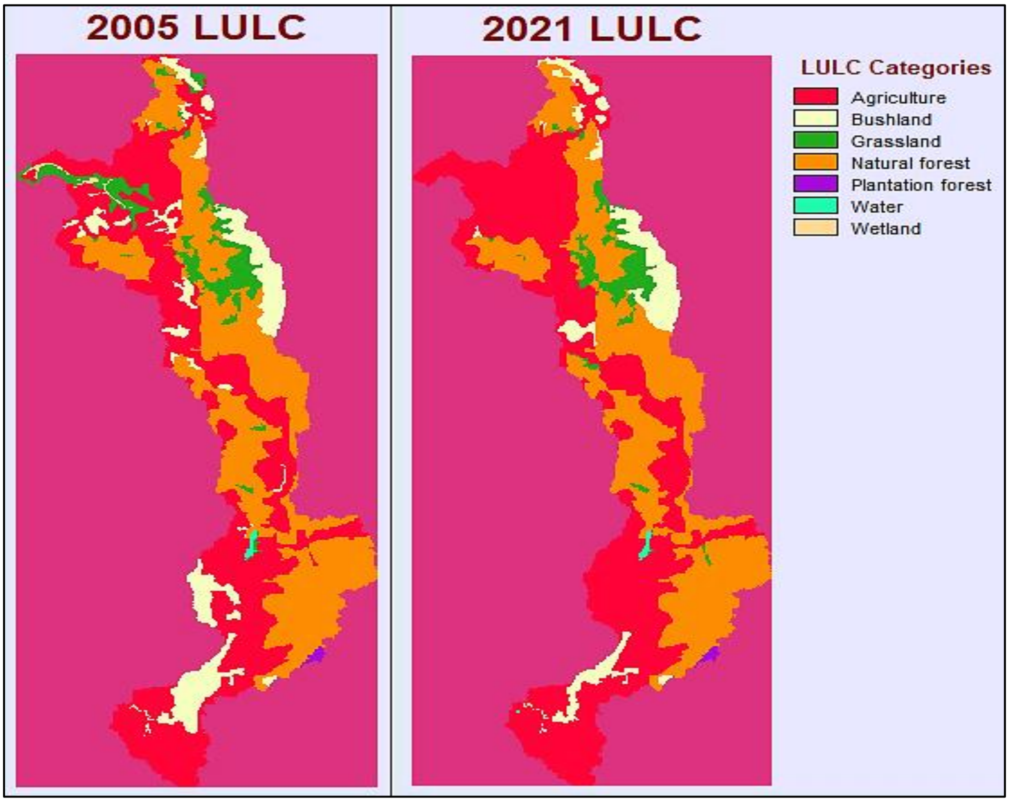

Figure 3: The 2005 and 2021 LULC in IDRISI format

The LCM change analysis panel provides a rapid assessment of quantitative change by illustrating gains and losses, net change and examining the contribution to changes experienced by single land cover by land cover categories. The transitions and exchanges that took place between the various land use/cover categories during the time interval were obtained both in map and graphical form (Figure 4).

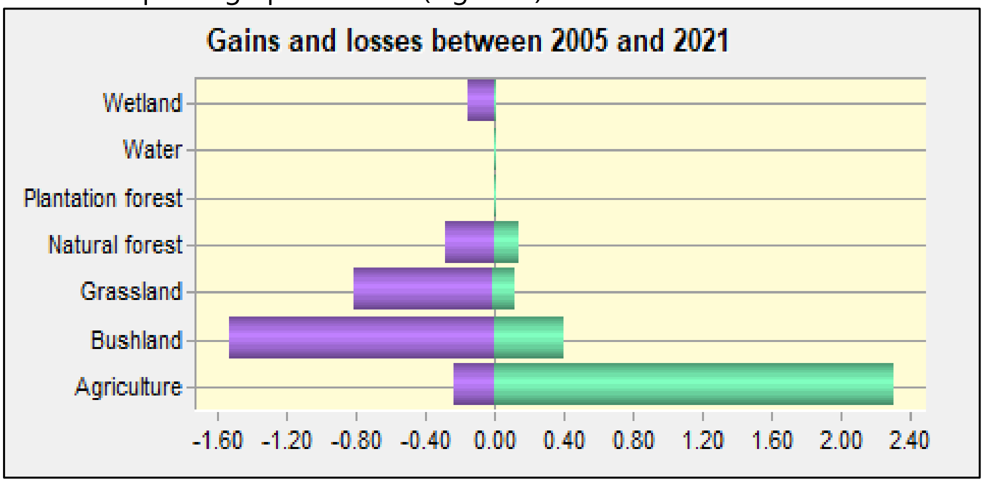

Figure 4: The LULC percent gains and losses

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All the land cover categories were used with transitions less than 0.50% of the total area ignored. The specific gains and losses of each LULC between 2005 and 2021 were: Agriculture lost -0.23% and gained 2.30%; Bushland lost -1.52% and gained 0.40%; Grassland lost -0.81% and gained 0.14%; Natural Forest lost -0.28% and gained 0.14%; and Wetland lost -0.15% and gained 0.00%. Two LULC categories of water and plantation forest remained constant over the periods.

The LULC driving factors used in the study were market centers, road network, river network, elevation and slope.

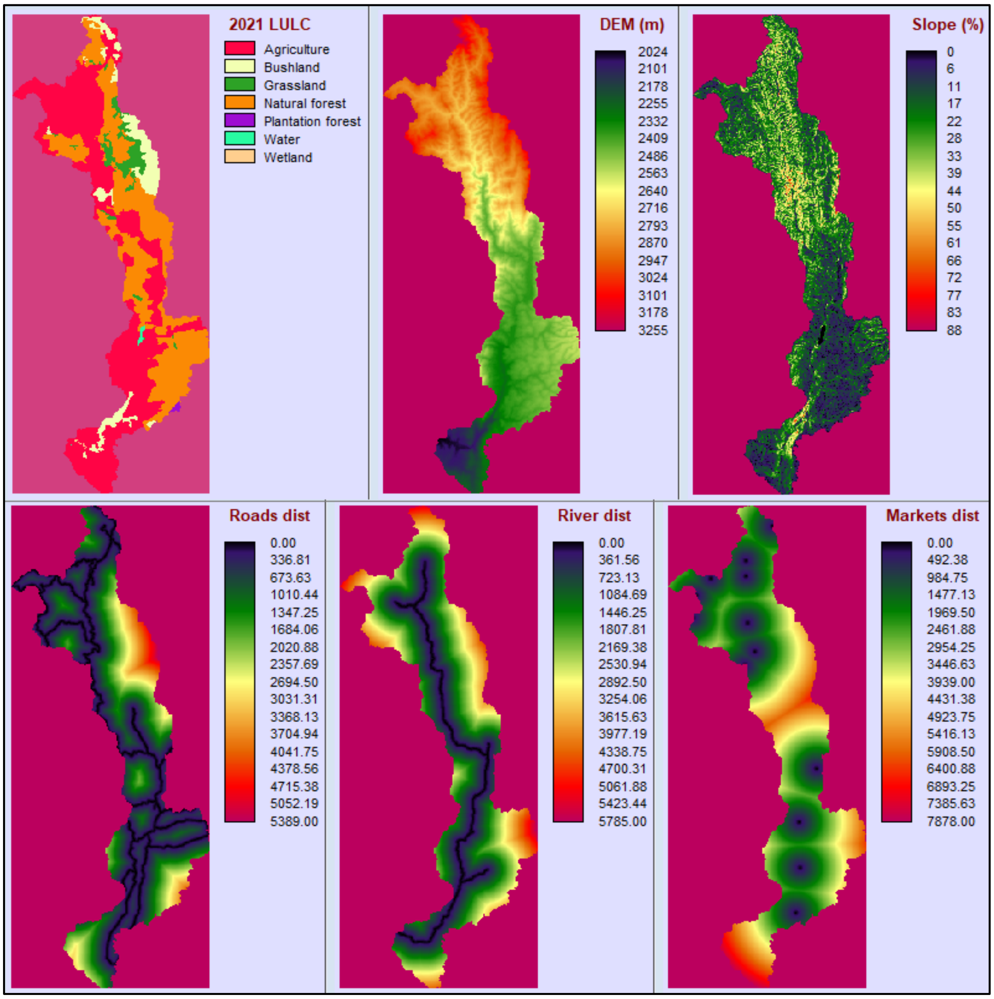

Figure 5: Variables' map used in LCM

These factors were generated with guidance from Google Earth Pro covering the entire watershed. The data were then processed to generate raster data based on the respective parameters which were distance in meters (market centers, road network, river network, meters above sea level (elevation) and

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percent rise (slope) (Figure 5). These LULC driving factors give a degree of suitability for an area to change (mostly on a distance basis).

The transition sub-model was developed using the Multi-Layer Perceptron (MLP) neural network. Moreover, MLP neural network is quite capable of modeling non-linear relationships and the most robust land cover change models (Eastman, 2012). The MLP neural network is one of the most commonly used Artificial Neuron Networks (ANN) (Rumelhart et al. 1986). The study LCM MLP iterations were set to 10000 which yielded an accuracy of 83.95% (Figure 6) a value satisfactory since it is higher than 80.00% (Eastman, 2012).

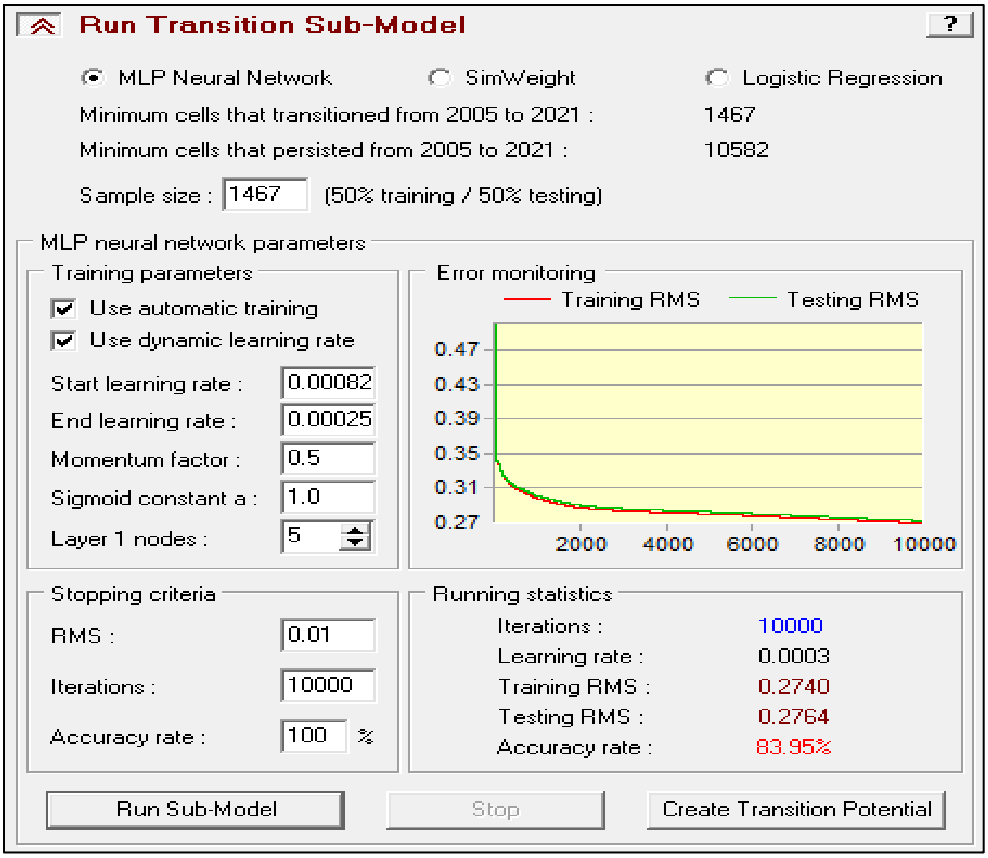

Figure 6: MLP neural network classifier process

The CA-Markov Chains predicted the 2055 LULC patterns in the watershed. Through analysis of 2005 and 2021 LULC data, the model identified the likelihood of a specific land cover type transitioning to another over a defined time frame in a specific area. The model calculates transition probabilities (Table 3.11) of the different LULC categories transforming into other LULC within a certain time interval. With these probabilities in hand, the model can then predict the most likely LULC configuration for the target year

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(2055) based on the current state (reflected in the 2021 LULC map) and the historical trends captured in the transition probabilities.

Climate Data Generation

The study used the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5) data available on the Consortium of International Agricultural Research Centers (CGIAR) website, http://cgspace.cgiar.org. The MarkSim DSSAT (Decision Support System for Agrotechnology Transfer) weather file generator was used to download the projected 2055 climate datasets.

The 2055 climate data was modeled following the Representative Concentration Pathway (RCP) 6.0 scenario which portrays a potential future Earth under a medium-high greenhouse gas (GHG) emissions trajectory (IPCC, 2014). The foundation for these projections lies in RCPs, a framework developed by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2014]. Compared to other RCPs, this scenario falls within the "medium-high emissions" category. It reflects a future with higher emissions than RCP 2.6 (low emissions) and RCP 4.5 (stabilization scenario), but lower than RCP 8.5 (high emissions) ([IPCC, 2014]).

This data was specifically generated for impact assessments, allowing researchers to evaluate the potential ramifications of climate change on various sectors like agriculture, water resources, ecosystems and even human health ([Rosenzweig et al., 2014 [Haines et al., 2014]). Additionally, RCP 6.0 data can inform the development of climate policies, allowing policy makers to assess the effectiveness of different greenhouse gas mitigation strategies in controlling future climate change (Rogelj et al., 2018). In the context of Elgeyo Marakwet County, where forest degradation, soil erosion, and changing agricultural practices continue to influence catchment dynamics, RCP 6.0 offers a suitable baseline for projecting water resource responses under moderate warming (Gichuki et al., 2021).

The DSSAT website offers a rich data set of climate variables with high spatial resolution and temporal coverage. Specifically, the downloaded daily precipitation and daily temperature data (minimum and maximum) covered a period from January 1st, 2050, to December 31st, 2059, which was then averaged to represent the 2055 climatic conditions. The climate data is provided in a gridded format and was downloaded at three points (with coordinates) (Table 1) distributed within the watershed.

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Table 1: Climate data points

Parameter	Name	Lat	Long
Precipitation and temperature	pcp35.48_0.85	0.85	35.48
Precipitation and temperature	pcp35.49_1.08	1.08	35.49
Precipitation and temperature	pcp35.46_1.18	1.18	35.46

The mean monthly climatological data set for the year 2055 is presented in Figure 7. Precipitation data shows that August will have the highest value, reaching 201.91 mm. Conversely, February has the least value of 43.26 mm. The temperature indicates that March will have the highest maximum temperature, reaching 23.2°C. In contrast, July displays the lowest maximum temperature, at a value of 19.3°C. The minimum temperatures indicate that April will have the highest value 9.9°C with the December recording of 9.2°C.

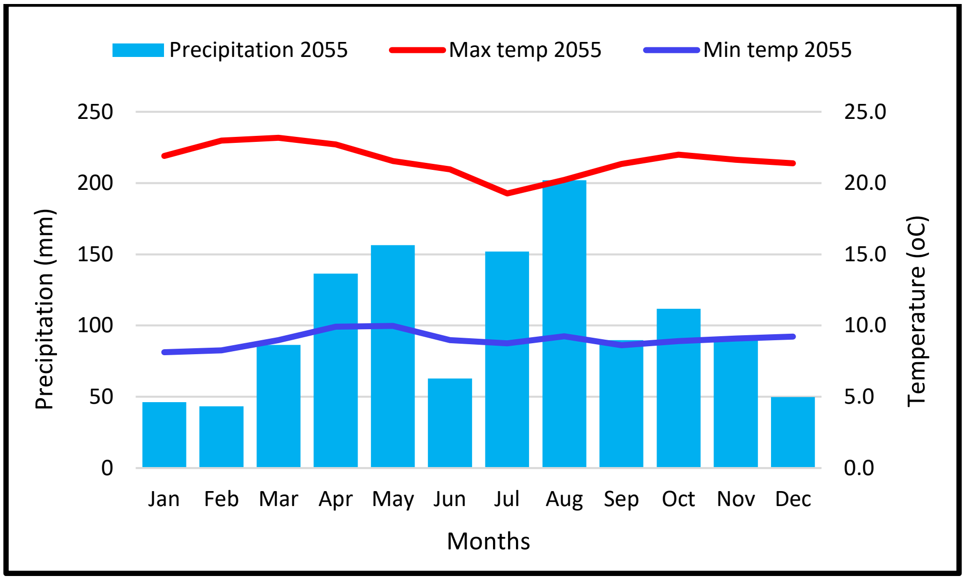

Figure 7: The 2055 mean monthly climate data

Projected 2055 Moiben River Flow

The 2055 SWAT model was constructed using the modeled 2055 LULC, the projected 2055 climate data sourced from digital elevation model (DEM) data downloaded from https://earthexplorer.usgs.gov/ and soils data sourced from https://swat.tamu.edu/data/. The SWAT model methodology and set-up were as described earlier.

Analysis of River Flow Variation

River flow analysis variations were conducted using Paired Sample t-test to test whether there is significant difference between the current and

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projected river flow volumes. The first sample covered Jan 2010-Dec 2018 with the second sample being the projected river flow covering Jan 2051-Dec 2059.

SWAT Hydrological Modeling

SWAT was run using 2055 LULC and climate datasets. Calibration (2010–2016) and validation (2017–2018) were previously completed for baseline assessment.

Results

Projected Land Use and Land Cover Dynamics in 2055 and Their Implications for Watershed Sustainability

The projected land use and land cover (LULC) pattern for the year 2055 indicates a continued dominance and expansion of agricultural land within the Moiben River watershed, accompanied by a steady decline in natural and plantation forest areas.

Table 2: Projected LULC in 2055

LULC Type	Area (ha)
Agriculture	46,839
Natural Forest	8,720
Grassland	4,981
Plantation Forest	1,217
Bushland	3,421
Water	442
Wetlands	1,097

As shown in Table 2, agricultural land is expected to increase to approximately 46,839 hectares, reflecting sustained population growth, rising food demand, and intensified farming practices. This expansion is projected to occur largely at the expense of natural forests, which are expected to shrink to 8,720 hectares, and plantation forests, which will decline further to 1,217 hectares. The reduction of these forested areas signals ongoing deforestation driven by farmland encroachment, settlement growth, and unsustainable timber extraction.

Grasslands are projected to decline to 4,981 hectares, while bushland will slightly contract to 3,421 hectares, suggesting further landscape homogenization as more natural vegetation is converted to cropland. Wetlands are estimated to occupy 1,097 hectares, indicating modest persistence due to limited protection measures, whereas water bodies remain relatively stable at 442 hectares, maintained mainly by the river network and

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small reservoirs. Hence, the 2055 LULC scenario suggests a watershed increasingly dominated by agriculture, with reduced vegetative cover and weakened ecosystem buffers. This transformation is expected to heighten surface runoff, sediment yield and nutrient loading into the Moiben River, potentially diminishing baseflow and water quality.

Future River Flow Simulation

The simulation of Moiben River flow for 2055, utilizing the projected land use/land cover (LULC) and corresponding climate data, forecasts a statistically significant alteration to the river's hydrological regime compared to the 2021 baseline (t-test=5.1418; p=0.0000). This future scenario is marked by increased seasonality and extreme variability.

Table 3: Moiben River 2021 and 2055 mean monthly river flows

Months	Year 2021	Year 2055	Change(m^3/s)	% Change
Jan	1.4	0.73	-0.67	-47.86
Feb	1.99	1.42	-0.57	-28.64
Mar	5.01	3.48	-1.53	-30.54
April	12.41	7.73	-4.68	-37.71
May	11.39	11.33	-0.06	-0.53
June	4.65	4.61	-0.04	-0.86
July	9.68	9.76	0.08	0.83
Aug	9.9	15.13	5.23	52.83
Sept	5.56	5.14	-0.42	-7.55
Oct	8.62	6.92	-1.7	-19.72
Nov	7.11	2.71	-4.4	-61.88
Dec	3.78	1.78	-2.0	-52.91

According to Table 3, the most notable shift is a sharp increase in discharge during the mid-year months of July and August, with August showing the most substantial surge of 5.23 m3/s (a 52.83% increase). This dramatic rise suggests intensified surface runoff, likely driven by the combined effects of reduced protective vegetation cover from LULC change and potential localized high-intensity rainfall events under the projected climate. However, the model predicts significant declines in flow during the traditional wet and transition seasons (March, April, October, November, and December). The sharpest reductions are projected for April (−37.71%) and November (−61.88%), indicating a severe reduction in water availability during these periods. This loss of flow is primarily attributable to diminished baseflow recharge resulting from the conversion of forests and natural cover, coupled with unfavorable changes in the seasonal distribution of rainfall. Months like May, June, and September show minor changes, suggesting some

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short-term flow resilience in the early dry season. Hence, the 2055 projections depict a watershed facing greater hydrological instability: reduced long-term recharge leads to lower flows during critical agricultural months, while rapid runoff causes sharper, intensified peak flows in others. These shifts have serious implications, including disrupted water supply, elevated soil erosion, and a heightened risk of flash floods.

Seasonal Variability and Projected Flow Dynamics of the Moiben River

The simulated future river flow for the Moiben River demonstrates a highly erratic seasonal pattern, a direct consequence of projected LULC changes and shifting climate regimes (Figure 8).

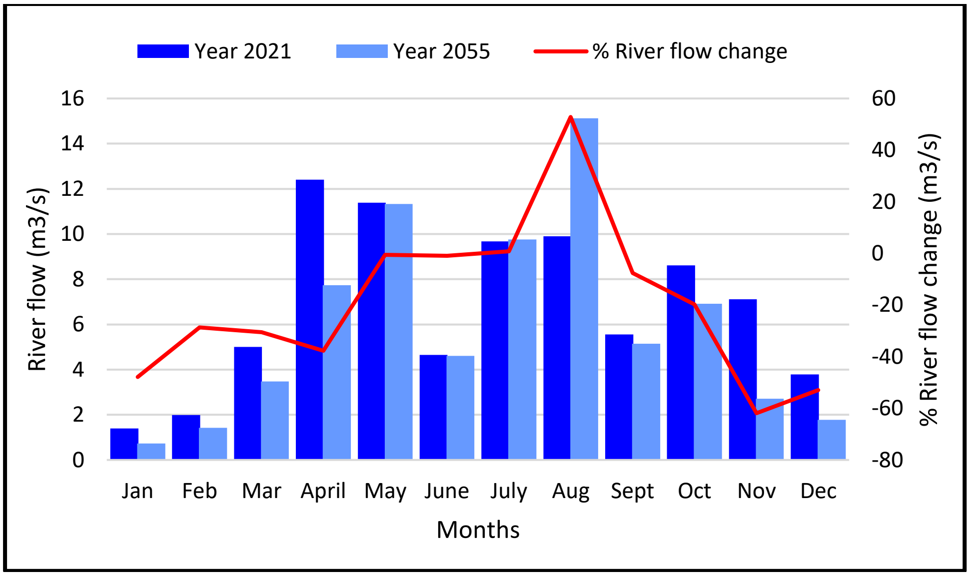

Figure 8. Simulated Monthly River Flow for 2021 and 2055

The first half of the year is characterized by prolonged hydrological stress: river discharge is predicted to fall consistently from January (a −47.86% drop) through June (a minimal −0.86% change). This trend signifies a substantial reduction in baseflow and groundwater recharge, likely due to factors like forest decline, expanded agriculture, and altered rainfall timing, all of which limit water infiltration. This indicates heightened water scarcity during the early part of the year, exacerbated by intensified evapotranspiration. A dramatic reversal occurs in August, which is projected to host the peak flow with a sharp 52.83% surge. This intense, short-lived peak is attributed to the combination of expected high-intensity rainfall and the watershed's diminished infiltration capacity (due to widespread cultivation and soil compaction). This translates to a flashier hydrological response with increased surface runoff. However, this surge is quickly followed by a steep decline that persists through December (falling to −52.91%), reflecting the

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rapid depletion of surface water stores and continued dry-season water loss. Hence, the 2055 projections point to a Moiben River with pronounced hydrological instability: extreme dry-season deficits are paired with intense, short-lived flood peaks. This amplified variability poses significant threats to water reliability for human uses, severely impacts aquatic ecosystems, and heightens the risk of erosion and sedimentation.

Discussion

The integrated CA–Markov–SWAT modeling framework revealed that the future of the Moiben River flow regime is characterized by statistically significant instability ($t=5.1418$, $p<0.001$), driven by the combined effects of Business-as-Usual (BAU) land-use change and projected RCP 6.0 climate variability. The analysis confirms a highly concerning trend of worsening dry season flow conditions concurrent with an amplification of peak flows, consistent with patterns observed globally and regionally (Pokhrel, 2018; Arnold et al., 1998).

The CA–Markov projection for 2055 signals a landscape under severe anthropogenic stress, with agricultural land expanding significantly at the expense of crucial Natural and Plantation Forests (Table 2). The loss of forest cover in critical recharge zones fundamentally alters the watershed's hydraulic properties, resulting in diminished infiltration and groundwater recharge. This process directly explains the severe projected decline in river flow during the long dry and transition months, particularly the drastic reductions in November (−61.88%) and December (−52.91%). Similar dry-season flow vulnerability due to deforestation and over-cultivation has been widely documented across Sub-Saharan Africa, including in Ethiopian watersheds (Gashaw et al., 2018; Abdule et al., 2023). The reduced baseflow component confirms a serious threat to water security, exacerbating water scarcity for irrigation and domestic uses, including the surrounding urban centers like Eldoret.

In stark contrast to the dry-season deficits, the simulation predicts a sharp, disproportionate surge in flow during August (+52.83%). This finding points to a watershed with increasingly flashy hydrological behavior, where short, intense rainfall events rapidly translate into surface runoff. This phenomenon is a direct consequence of the widespread agricultural expansion and associated soil compaction, which significantly reduces the soil's capacity to absorb water. The conversion of high-infiltration covers (forest/grassland) to cultivated fields increases the effective runoff (Li et al., 2020). This amplification of peak discharge mirrors findings from other basins where land-use intensification increased flood peaks (Ji et al., 2021; Githui et al., 2009). The August spike thus suggests a heightened risk of flash floods,

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accelerated soil erosion, and sedimentation, which will further degrade the river's ecological integrity and water quality (Kamamia et al., 2022; Mutua et al., 2009).

The complex temporal pattern of flow decline affecting most months, including the traditional wet seasons (e.g., April at −37.71% and March at −30.54% suggests a significant interaction between LULC degradation and the RCP 6.0 climate scenario. While LULC predisposes the watershed to poor infiltration, future climate variability (e.g., changes in the frequency or intensity of rainfall) likely dictates the ultimate magnitude and timing of the flow deficits (Pokhrel, 2018). Comparatively, the Moiben results reinforce established trends in Kenyan basins, where LULC changes linked to high peak flows and reduced dry-season discharge have been observed in the Nzoia and Mara systems (Kibiiy et al., 2021). The projected hydrological imbalance therefore constitutes a serious challenge to maintaining healthy river flow levels and water security throughout the region.

Conclusion and Policy Implications

This study conclusively demonstrates the profound and interconnected roles of land use change and climate variability in determining the future hydrological fate of the Moiben River. The integration of the CA-Markov and SWAT models for scenario simulation revealed that the Business-as-Usual (BAU) scenario characterized by persistent agricultural expansion and deforestation will lead to a significantly destabilized flow regime by 2055. The simulated hydrological response shows a perilous combination of severe dry-season flow deficits (reflecting diminished baseflow and groundwater recharge) and amplified flash flood peaks (due to increased surface runoff), confirming a critical impairment of the watershed's natural resilience. This finding indicates that unregulated land use is the single greatest threat to sustaining future streamflow and overall watershed health, necessitating an urgent shift toward evidence-based conservation.

The findings advocate for the immediate institutionalization of watershed management frameworks at the county level that are anchored in these predictive insights. The policy response must center on establishing land use zoning that aligns with hydrological sensitivity, specifically restricting development in critical recharge areas and strengthening the enforcement of riparian buffer protection to maximize infiltration and reduce erosion risk. Policies must actively promote afforestation and agroforestry programs in the upper watershed to enhance soil water storage and stabilize seasonal discharge variability. Furthermore, to ensure adaptive capacity, there must be sustained investment in hydrological monitoring and modeling capacity within key water management agencies. Finally, successful translation of these

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model-based insights into tangible outcomes requires that sustainable land use governance in the Moiben watershed be robustly integrated into Kenya's existing policy frameworks, including the Water Act (2016), Climate Change Act (2016), and the National Land Use Policy (2017). Collaborative planning involving local government, researchers, and community stakeholders is essential for translating this predictive science into actionable strategies that secure long-term water security and protect the ecosystem health of the Moiben River.

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