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Impacts of land use and climate change on streamflow and hydrological droughts in the Küçük Menderes Basin, Türkiye: A future outlook

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Abstract: This study assesses the influence of land use and climate change on streamflow and hydrological droughts in the Küçük Menderes Basin, located in western Türkiye. Despite its fertile lands and diverse agricultural activities, the basin faces challenges due to its semi-arid climate and the adverse effects of climate change on soil moisture and water availability. Shifts in land use, transitioning towards industrial or residential areas, further compound these challenges. Using the Soil and Water Assessment Tool (SWAT), streamflow is simulated for the period 2025-2099 under various climate and land use change scenarios. Climate data for these simulations was downscaled to a 1 km resolution through the double nesting method, utilizing the RegCM4.4 regional model and incorporating global outputs from the MPI-ESM-MR model under the RCP8.5 scenario. Drought analyses are conducted using the Standardized Streamflow Index (SSFI), revealing projected decreases in surface water quantities, ranging from 2% in the short term to up to 80% by 2100. The Mann-Kendall test applied to SSFI values indicates an increasing trend in drought, whether considering isolated impacts of climate change or integrated impacts of climate and land use changes. However, when only land use change is considered, the SSFI drought index exhibits lower values, despite a decreasing trend appearance in drought emergence.

Key words: Basin modeling; Soil and Water Assessment Tool (SWAT); climate change; land-use change; drought; Standardized Streamflow Index (SSFI).

1. INTRODUCTION

This study examines the impacts of land use and climate change on streamflow and hydrological droughts in the Küçük Menderes Basin, situated in western Türkiye. Known for its fertile lands and diverse agricultural activities, including crops with high economic value and silage crops crucial for large-scale livestock, the basin faces challenges due to its semi-arid climate and the adverse effects of climate change on soil moisture and water resources availability (Rossi et al.,2023). Furthermore, significant shifts in land use, transitioning from agriculture to industrial or residential areas, further exacerbate these challenges. Considering these reasons, the basin emerges as a hotspot at risk from emerging climatic and land-use-related instabilities, warranting detailed examination. Understanding how the hydrological regime and water resources will be affected by climate variability and change, as well as shifts in land-use composition, is crucial for developing reliable adaptation strategies in water management (Krysanova and White, 2015).

The IPCC's (International Panel on Climate Change [IPCC], 2023), AR6 Synthesis Report stated 1.5°C rise in climate change by 2021-2040, posing significant threats to ecosystems and human well-being. From 2041 to 2100, climate change consequences will intensify due to human-induced activities like deforestation, disrupting the planet's energy balance (Türkeş, 2022).

The Soil and Water Assessment Tool (SWAT) is widely used for basin modeling (Narsimlu et al., 2013; Krysanova and White, 2015; Anand et al., 2018; Rodrigues et al., 2019; Zhang et al., 2020; Abbaszadeh et al., 2023) due to its extensive application and high accuracy in simulating complex hydrological processes. Trambauer et al. (2013) identified SWAT as one of the most suitable models for drought forecasting in Africa due to its capacity to address relevant processes and operational feasibility. Narsimlu et al. (2013) highlighted the need for adaptation strategies like soil conservation and drought-resistant crop cultivation to mitigate future hydrological changes due to climate change. Krysanova and White (2015) highlighted the significance of incorporating both climate change and land use change in hydrological modeling to accurately forecast future water resource availability. Anand et al. (2018) pointed out that urbanization and increasing demands for irrigation are significant factors in causing water scarcity and emphasized the importance of assessing land use changes' impacts on local hydrology to inform sustainable water resource strategies. Rodrigues et al. (2019) simulated the hydrological patterns using SWAT and indicated potential decreases in streamflow and water budget throughout the 21st century under different climate change scenarios, with significant implications for water availability and ecological health. According to Zhang et al. (2020), afforestation increased evapotranspiration and decreased surface runoff while urbanization increased surface runoff and decreased lateral runoff and groundwater. Samavati et al. (2023) performed SWAT model to assess the impacts of climate change on runoff in the Alvand Mountain Basin, finding significant reductions in annual runoff and increasing drought intensity under various climate scenarios, particularly with the Miroc5 model predicting an 8.36% annual decrease and up to 335% reduction in monthly runoff during September by 2040. Abbaszadeh et al. (2023) studied examines the impacts of climate change and Land Use/Land Cover (LULC) changes on hydrology in the Minab River Basin, Iran, projecting significant increases in precipitation and temperature, which are expected to raise evapotranspiration by up to 12.8% and reduce streamflow by 2–11% due to LULC changes, with temporal variations in streamflow responses influenced by different climate scenarios.

The Standardized Streamflow Index (SSFI), developed by Modarres (2007), is utilized for the analysis of hydrological drought. The SSFI, recommended by the World Meteorological Organization and Global Water Partnership (WMO and GWP, 2016), is extensively utilized (Hosseinzadeh Talaee et al., 2014; Huang et al., 2015; Rodrigues et al., 2019; Tenagashaw and Andualem, 2022).

In the present work, an integrated assessment framework was introduced to evaluate the combined impacts of land use and climate change on streamflow and hydrological droughts in the Küçük Menderes Basin, Türkiye. The basin modeling for the future timeframe incorporated land use maps for the years 2035, 2065, and 2085, representing the short term (2025-2049), medium term (2050-2074), and long term (2075-2099), respectively. Utilizing the Soil and Water Assessment Tool (SWAT) and downscaling climate data to a 1 km resolution with the RegCM4.4 model, the streamflow was simulated for the period 2025-2099 under various scenarios. The utilization of the Standardized Streamflow Index (SSFI) enhances the understanding of how climate variability and land use changes interact to drought, underscoring the urgent need for adaptive water management strategies in this semi-arid region. This study provided a comprehensive perspective on hydrological responses to both climate change and land-use modifications, making it a significant resource for policymakers and stakeholders involved in water resource management.

2. MATERIALS AND METHODS

2.1 Study area

The Küçük Menderes Basin presented in Figure 1 is located in the western Türkiye, between the Büyük Menderes and Gediz Basins and covers mostly the province of İzmir. The river length is about 129 km and the basin area is approximately 3,450 km^2. The basin consists of 58.6% agricultural, 20.3% pastures and 16% forest areas (Figure 1).

2.2 Data

The SWAT model basically requires digital elevation model (DEM), land use, soil map, and climate data which includes precipitation, maximum and minimum air temperatures, wind speed, solar radiation, and relative humidity given by Table 1. The DEM of the Küçük Menderes Basin was obtained at a resolution of 5 km x 5 km and 10-meter elevation range using local maps. The input data for the modelling phase of the reference period were obtained from the meteorological and flow observation stations provided by the Turkish State Meteorological Service and State Hydraulic Works, which are recorded daily in the basin shown in Figure 1. The soil database was derived using the SoilGrids (ISRIC World Soil Information, 2020) database with a 250 m grid resolution. The land use data utilized in this study was obtained from the CORINE Land Cover (LC) map, which is generated by the Copernicus Land Monitoring Service (European Environment Agency, 2006). The CORINE LC 2006 map was utilized for modeling purposes for the time frame of 2000-2012, with the CORINE LC 2000 map serving as the reference period. Crop pattern and irrigation system information were obtained from State Hydraulic Works (DSİ). Future meteorological data encompassing total precipitation, maximum and minimum temperature, shortwave solar radiation, relative humidity, and wind speed, which originated from the RegCM4.4 version regional model to downscale the global climate data to 1 km resolution through the double nesting method, was prepared by compiling the global outputs of the MPI-ESM-MR model with the RCP8.5 scenario. The basin's high vulnerability to extreme climate outcomes, where the severe scenario provides insight into the upper bounds of potential impacts, and limitations in resources required a streamlined approach for computational feasibility. The land use maps of the years 2035, 2065 and 2085 were predicted through the land use change modeling efforts that were conducted by a neural network and Markov Chain-Cellular Automata based built-in module of TerrSet software called Land Change Modeler (LCM).

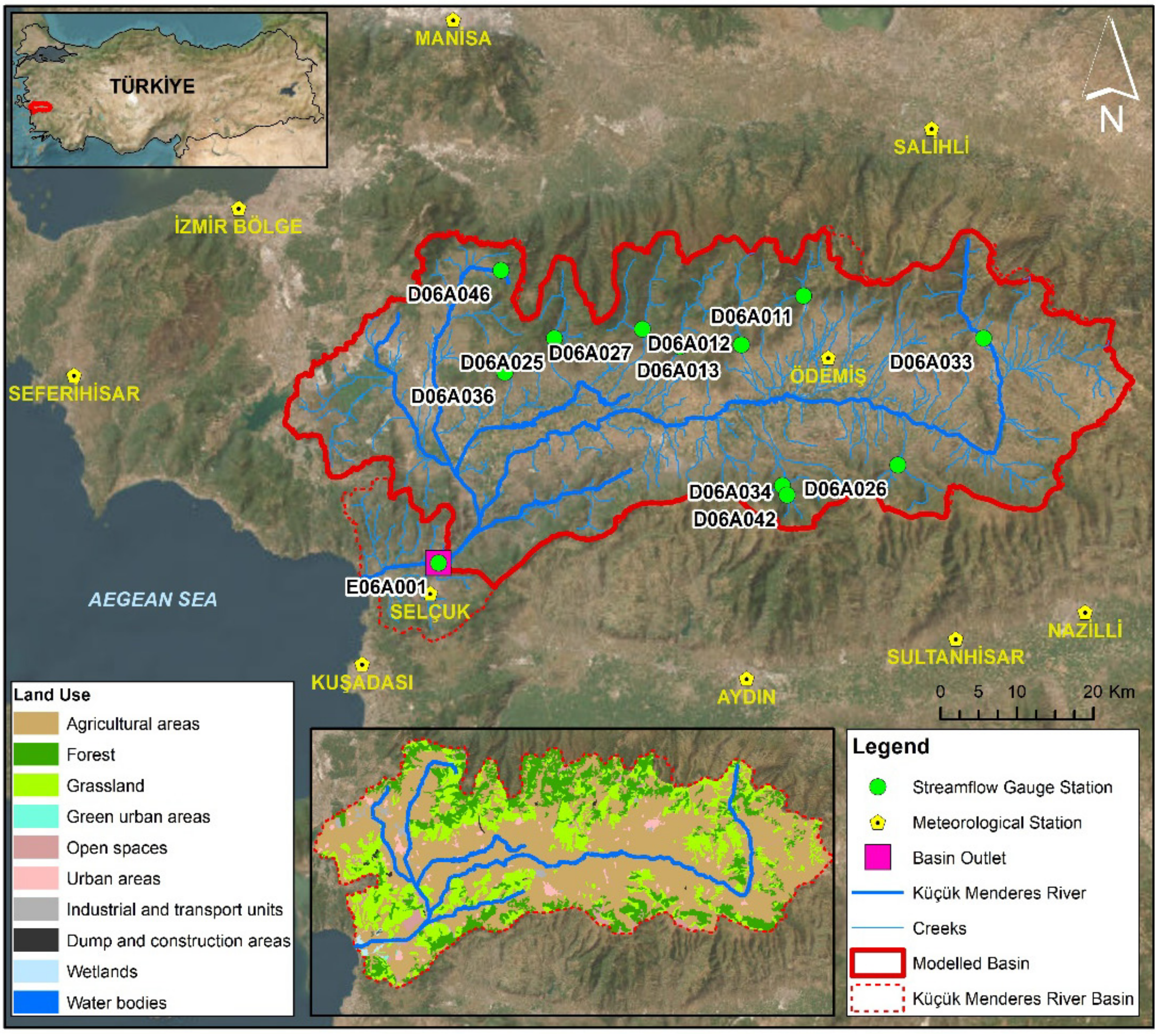


Figure 1. The location and land use of Küçük Menderes Basin.

Table 1. SWAT data and their respective sources.

Data	Source	Data Type	Description
Digital Elevation Model (DEM)	Local maps in 1/5000 scale	Raster (gridded)	5 km x 5 km resolution.
Streamflow Gauges	General Directorate of State Hydraulic Works (DSİ)	Point-based, daily time series	Observed streamflow data of 12 flow stations (1953-2018).
Observed Meteorological Data	Turkish State Meteorological Service (MGM)	Point-based, daily time series	Total precipitation, maximum and minimum temperature, shortwave solar radiation, relative humidity, and wind speed data of 11 meteorological stations (1960-2018).
Climate Data	MPI-ESM-MR model (RCP 8.5 scenario)	Netcdf, daily time series	Total precipitation, maximum and minimum temperature, shortwave solar radiation, relative humidity, and wind speed data for the reference period (1985-2009) and the future periods (2025-2099).
Soil Data	ISRIC World Soil Information's Purpose and Strategy	Raster (gridded)	250 m gridded data for 7 layers for 200 cm depth.
Land Use	CORINE Land Cover by Copernicus Land Monitoring Service.	Vector (polygon)	For the years 2000 and 2006 (used for reference (1985-2009) and calibration-validation periods (2000-2012), respectively).
Crop pattern	General Directorate of State Hydraulic Works (DSİ)	List	General irrigation information (Crop pattern and irrigation period, irrigation system and water source).

2.3 Methodology

In the study, the Soil and Water Assessment Tool (SWAT) developed by Arnold et al. (1998) was applied to Küçük Menderes Basin for assessing land use and climate change impacts on streamflow quantities and associated drought appearances. The modeling flowchart is depicted in Figure 2. It requires detailed data on meteorological conditions, soil properties, topography, vegetation, and land management, and operates on a water balance equation. In modeling the Küçük Menderes River Basin, 1,088 Hydrologic Response Units (HRUs) were created across 50 sub-basins, using specific thresholds for land use, soil, and slope combinations. Data from 10 meteorological stations were incorporated, and the model was executed for 2000-2012, with the first year as a warm-up period.

Sensitivity analyses were conducted based on t-tests and p-values using both Global and One-at-a-Time methods to identify parameters for calibration and validation, where Global sensitivity analysis evaluates all parameters simultaneously, and One-at-a-Time analysis focuses on individual parameters.

Afterwards, the outputs obtained were used to perform sensitivity analysis, calibration, and validation processes in a sequential manner using SWAT-CUP, developed by Abbaspour (2015), with Sequential Uncertainty Fitting Algorithm (SUFI2). The calibration was run for the period 2001-2007, by comparing the simulated streamflow by model and observed data recorded at the basin outlet (E06A001 flow station) shown by Figure 1. The Nash Sutcliffe Efficiency (NSE) and determination coefficient (R^2) were used to detect model performance. Following the calibration, validation was conducted for the period from 2008 to 2012. Using the parameter values that were optimized through these procedures, the SWAT model was run separately for future time periods.

Land use and climate change patterns were assessed toward three subsequent horizons: (a) Short term (2025-2049), (b) Medium term (2050-2074) and (c) Long term (2075-2099) periods. Consequently, projections were conducted for the streamflow under various scenarios, considering changes in climate and land use.

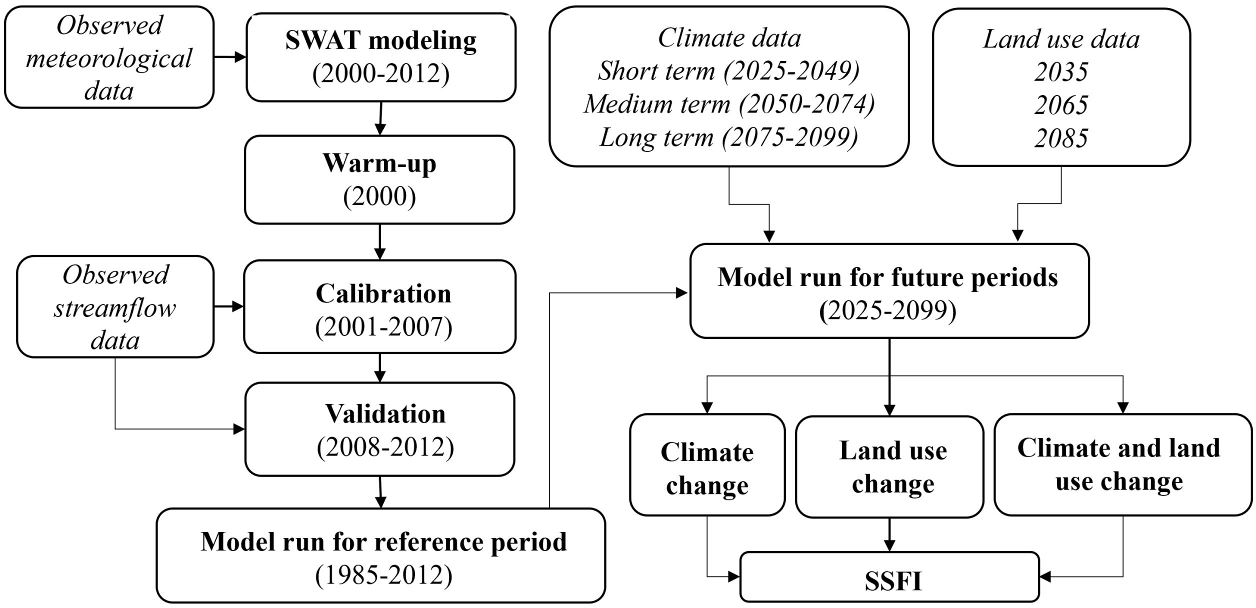


Figure 2. Flowchart of the methodology.

The Standardized Streamflow Index (SSFI), which is based on the same calculation steps as the Standardized Precipitation Index (SPI) presented by McKee et al. (1993), was used to examine hydrological droughts emerge, develop, and further intensify under climate and land use change impacts. In doing so, climate and land use-driven enhancing impacts were examined both separately and through an integrated consideration. SSFI addresses hydrological drought and uses the SPI program with flow data. The SPEI package in the R statistical program was used in the calculation. The SSFI for a given period is calculated as the streamflow difference divided by the mean and standard deviation (Equation 1).

$$SSFI = \frac{F_i - \bar{F}}{\sigma} \quad (1)$$

where, F_i is the streamflow discharge in time interval, $\bar{F}$ the series mean and σ is the standard deviation for series (Modarres, 2007). The classification intervals of SSFI are the same as the SPI classification recommended by McKee et al. (1993).

The SSFI series indices were assessed for a monotonic trend with a 0.05 significance level using the Mann-Kendall nonparametric test (Mann, 1945; Kendall, 1948). The test was conducted using the "trend" package in R statistical program.

3. RESULT AND DISCUSSION

3.1 SWAT modeling

In the basin modeling process, station E06A001, located at the outlet of the Küçük Menderes River Basin, was specifically designated as the basin outlet. Hydrological processing units (HRUs) were generated using a multiple HRU methodology, resulting in a total of 1088 HRUs spread across 50 sub-basins. This generation process involved applying specific thresholds: 5% for land use, 10% for soil, and 5% for slope combinations given by Figure 3. Data and locations from 10 meteorological stations, including long-term measurements, were incorporated into the model. The SWAT model was executed for the period between 2000 and 2012 by regarding the first year as the warm-up period.

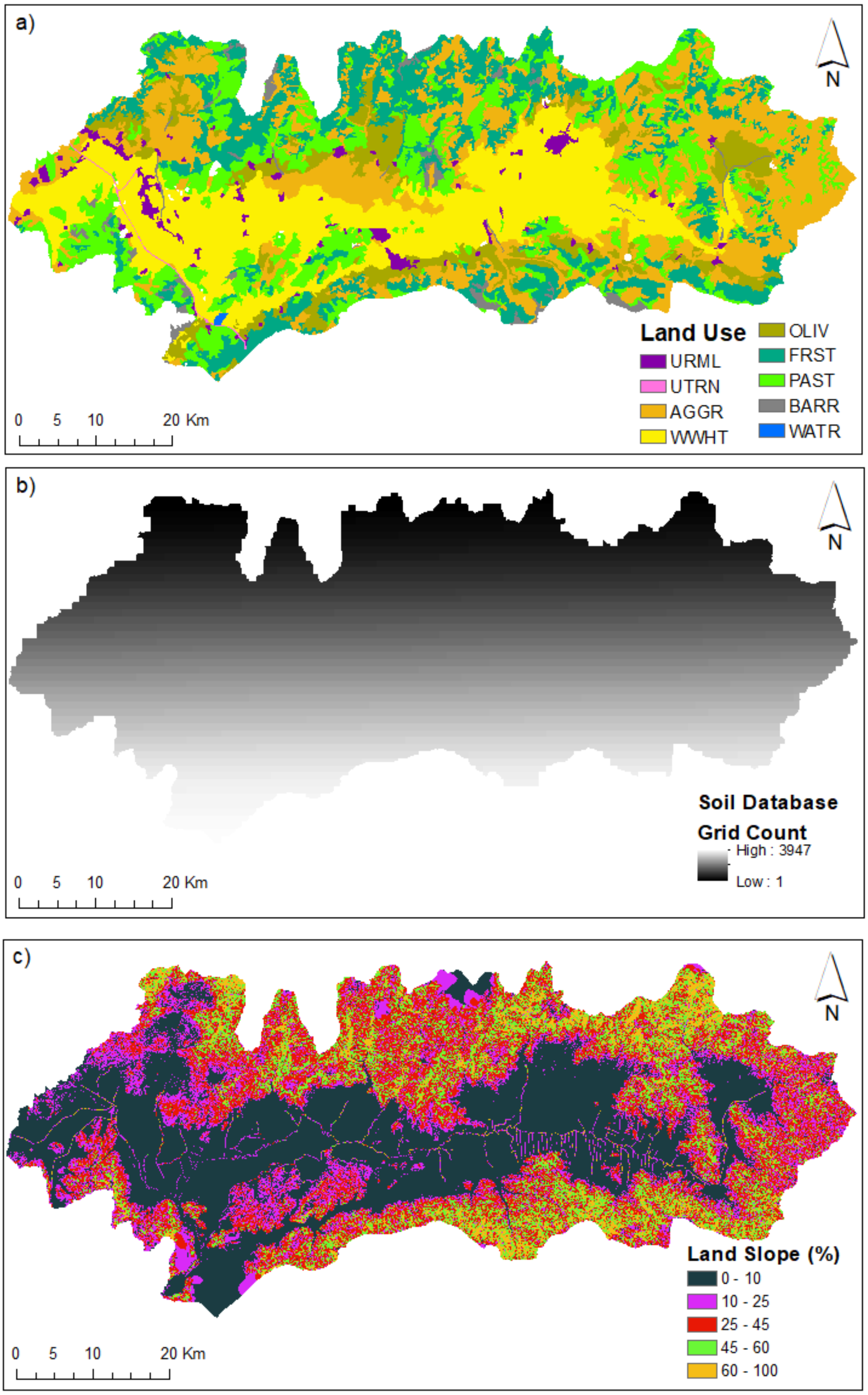


Figure 3. a) Land use map, b) soil map, c) land slope map.

After model run, both the Global and One-at-a-Time sensitivity analyses were conducted, Figure 4 shows the results of sensitivity analysis based on One-at-a-Time method. A total of 14 parameters and their values were identified and listed for calibration and validation (Table 2). Figure 5 shows the calibration and validation results of the SWAT model after sensitivity analysis. Calibration of the model resulted in Nash-Sutcliffe Efficiency (NSE) of 0.81 and coefficient of determination (R^2) of 0.81 (Figure 5a), while validation yielded NSE=0.86 and R^2=0.90 (Figure 5b), categorizing the model performance as "very good" based on NSE and R^2 values according to Moriasi et al. (2007). After establishing a satisfactory level of consistency between observed and simulated streamflow time series, various land use and climate change scenarios were subsequently applied.

The assessment of climate change impact utilized outputs from the MPI-ESM-MR model with the RCP 8.5 scenario, incorporating land use change maps for the years 2035, 2065, and 2085 generated using the Land Change Modeler (LCM) module in TerrSet, which applies neural networks and Markov Chain-Cellular Automata for land use change modeling. Future basin modeling employed land use maps corresponding to short-term (2025-2049), medium-term (2050-2074), and long-term (2075-2099) periods.

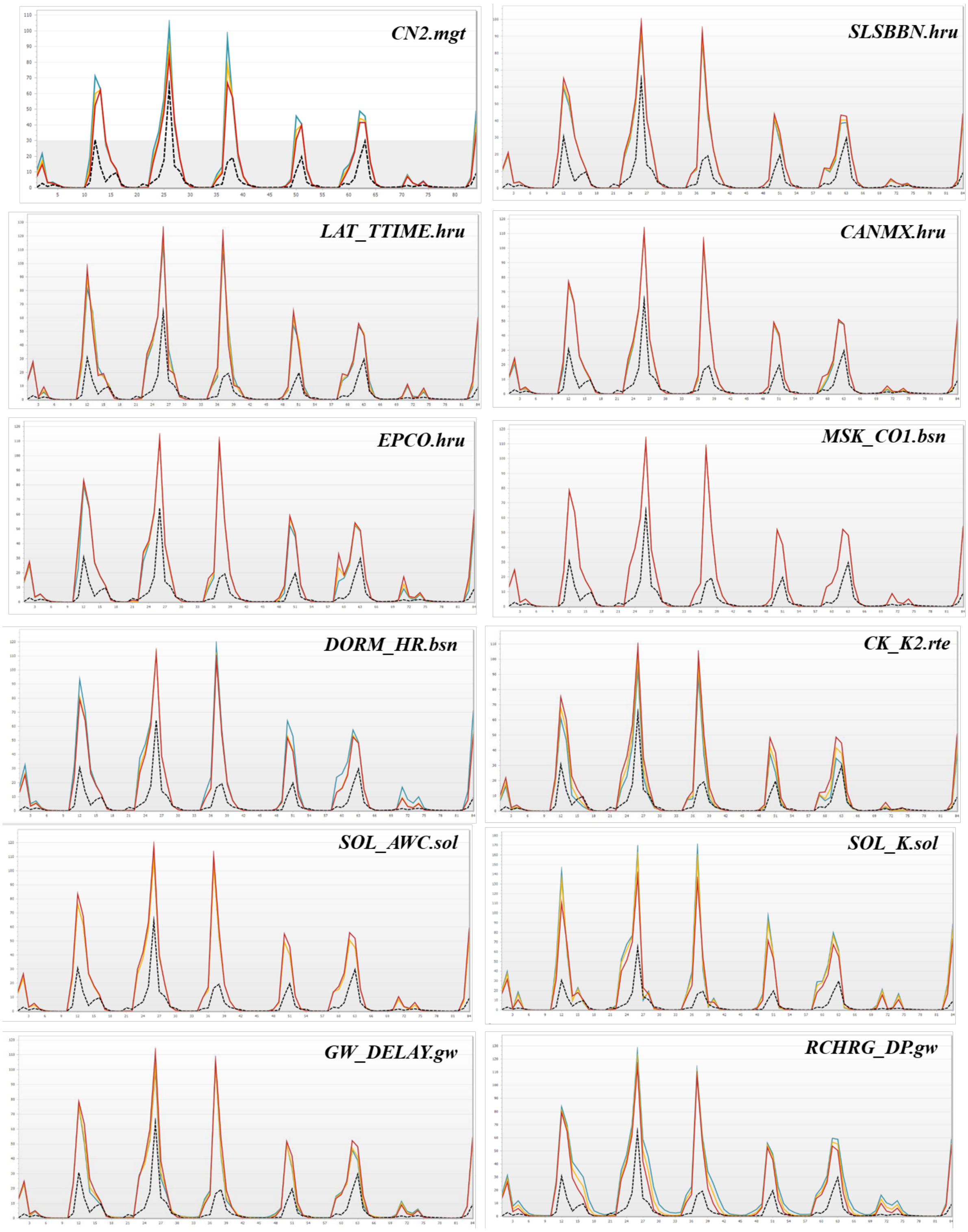
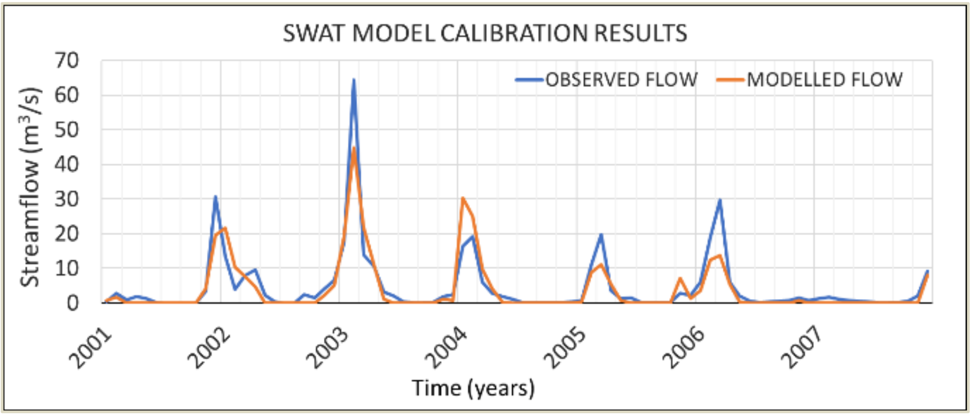


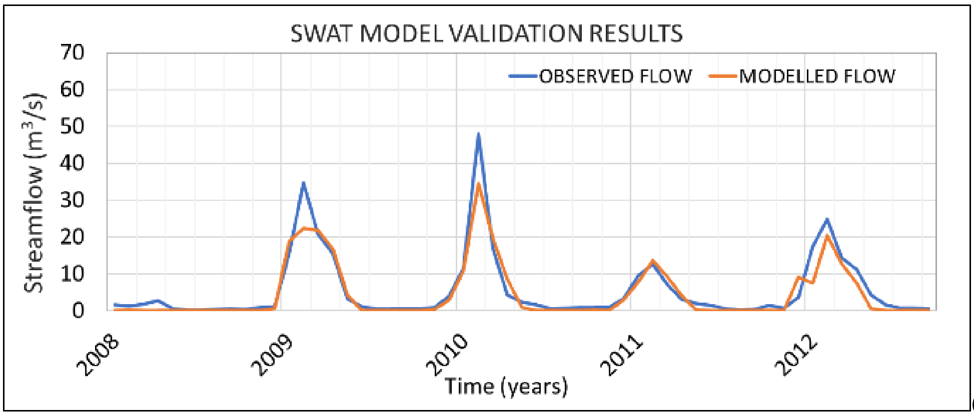
Figure 4. One-at-a-Time sensitivity analysis.

Table 2. Sensitive parameters and their calibrated values

Parameter	Group	Description	Method	Method Value	Parameter Values		Reference Values	
					Min	Max	Min	Max
CN2.mgt	Management	Initial SCS curve number for moisture condition II	r	-0.39	36.6	59.79	25	98
SLSUBBSN.hru	HRU	Average slope length (m)	r	1.253	20.28	135.78	10	150
LAT_TTIME.hru	HRU	Lateral flow travel time (days)	a	13.656	13.66	13.66	0	180
CANMX.hru	HRU	Maximum canopy storage (mm H_2O)	a	17.395	17.4	17.4	0	100
EPCO.hru	HRU	Plant uptake compensation factor	r	-0.164	0.84	0.84	0	1
MSK_CO1.bsn	Basin	Calibration coefficient used to control impact of the storage time constant (Km) for normal flow	r	1.628	1.97	1.97	0	10
DORM_HR.bsn	Basin	Time threshold used to define dormancy (hours)	a	9.062	9.06	9.06	0	24
CH_K2.rte	Transport	Effective hydraulic conductivity in main channel alluvium (mm/hr)	a	4.287	4.29	4.29	-0.01	500
SOL_AWC.sol	Soil	Available water capacity of the soil layer (mm H_2O/mm soil).	r	0.478	0.38	0.61	0	1
SOL_K.sol	Soil	Saturated hydraulic conductivity (mm/hr)	r	0.004	0.14	0.69	0	2000
GW_DELAY.gw	Groundwater	Groundwater delay time (days)	r	0.849	57.33	57.33	0	500
RCHRG_DP.gw	Groundwater	Deep aquifer percolation fraction	r	3.77	0.24	0.24	0	1
GWQMN.gw	Groundwater	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O)	r	-0.002	998.26	4991.31	0	5000
GW_REVAP.gw	Groundwater	Groundwater "revap" coefficient	r	5.144	0.12	0.12	0.02	0.2



(a)



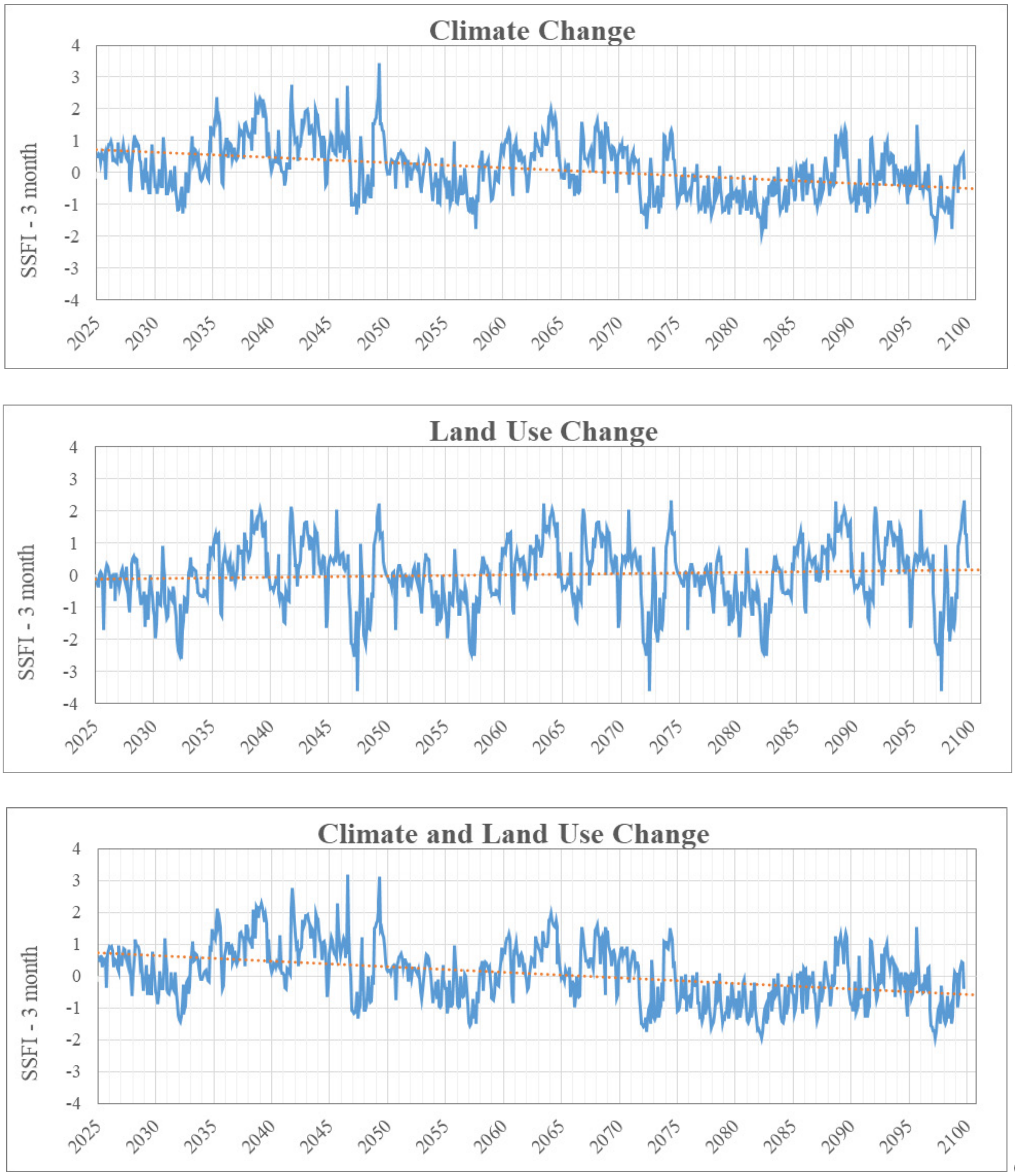
(b)

Figure 5. Calibration (a) (NSE=0.81 and R^2=0.81) and validation results (b) (NSE= 0.86 R^2=0.90) of the SWAT model for Küçük Menderes River basin outlet.

3.2 Hydrological drought analysis

The SSFI values calculated through 3-month windows (i.e. SSFI-3) over simulation outputs under (a) land use change, (b) climate change and (c) combined land use and climate change scenario effects are shown in Figure 6. A 3-month timescale is suitable for assessing short-term hydrological responses to both climate and land use changes, which are especially relevant in the semi-arid Küçük Menderes Basin, where rapid seasonal shifts in water availability are common.

SWAT simulations provide informative outputs that distinguish between the impacts solely resulting from hydro climatic impacts, those that are contributed by the driven land use patterns and the total patterns that consider integrated impacts. Always with respect to the conditions of the reference period, the model outputs reveal reductions in the projected monthly average stream flows in quantities varying between 15% and 90% when only the changing climatic conditions are taken into consideration.



(a)

(b)

(c)

Figure 6. SSFI-3 series for the conditions under: (a) Climate change, (b) Land use change, (c) Both climate and land use change (Küçük Menderes River basin outlet).

The study mainly assessed the integrated impacts of climate and land use change and predicted decreases in surface water quantities in the basin in levels ranging from only 2% in the short-term period to more remarkable rates by 80% in the longest period toward the horizon 2100 (see Figure 6). By applying Mann-Kendall test to the SSFI values given in Figure 6, an increasing trend in drought is revealed both under the isolated impacts of climate change and in the case when the integrated impacts of climate and land use changes are counted. For the sole consideration of the land use change aspect (Figure 6b), it is seen that the SSFI drought index holds much lower values when compared to the results obtained from other scenarios, even though there happens to be a decreasing trend appearance in drought emergence.

3.3 Discussion

Samavati et al. (2022) performed SWAT model and indicated an annual decrease for streamflow of 8.36%, with the most significant seasonal reduction observed in summer, reaching up to 75%. Monthly variations were even more pronounced, with a 79% decline in April and an increase of 335% in September under the Miroc5 (RCP8.5) scenario. Also, they showed that there were no significant trends in the reference period and, but the future drought intensity indicated the increasing trend under all scenarios studied.

Tenagashaw and Andualem (2022) performed SWAT model and projected monthly streamflows under the RCP 4.5 emission scenarios using CORDEX-Africa program for climate data for the periods 2011–2031, 2032–2052, and 2053–2073 with the reference 1986–2005 in the Lake Tana sub-basin. The study indicated an increase in streamflow from January to May and October to December, suggesting improved water availability during these periods. However, there was a concerning decrease in streamflow during the rainy season from June to September, which could lead to water shortages when demand is highest. They evaluated the drought severities and durations using SSFI for the future periods.

Abbaszadeh et al. (2023) investigated the future climatic conditions of the Minab River Basin, Iran, by considering three CMIP6 scenarios (SSP1-2.6, SSP3-7.0, and SSP5-8.5 scenarios) from the CanESM5 model during 2021–2050 and 2051–2080.They showed the significant effects of climate change and Land Use/Land Cover (LULC) changes on the hydrology of the Minab River Basin (MRB). Future projections indicate an 88% increase in precipitation and rises in temperatures of 21% and 12% for minimum and maximum values, respectively. These climatic changes are expected to increase evapotranspiration (ET) by 12.8% due to climate factors and 2–6% from LULC changes, which could reduce streamflow by 2–11%, particularly in dry seasons. While climate change may increase streamflow under most scenarios, significant variations occur by season and scenario, with the SSP5-8.5 scenario showing the only increase during the 2050s.

In this study the SWAT model also applied, but focused on both land use changes and climate variability's effects on streamflow and hydrological droughts. The incorporation of the 3-months SSFI in the Küçük Menderes study allowed for a more comprehensive analysis of short-term drought intensity and its trends, providing insights into the interconnected challenges in a season of climate change and land use dynamics.

4. CONCLUSION

This study emphasizes the Küçük Menderes Basin’s heightened vulnerability to climate and land use changes, which together pose significant risks to streamflow and hydrological drought resilience. Projections using the SWAT model for 2025-2099 indicate substantial reductions in streamflow, with potential declines reaching 20% in the short term and exceeding 80% by 2100 due to climate change impacts. Land use transitions, including decreased irrigation and expanded urbanization, introduce mixed effects on streamflow, somewhat alleviating flow reductions by 10-15% through modified surface runoff. However, the integrated influence of these changes reveals an intensifying drought trend, corroborated by the SSFI drought index and Mann-Kendall test results. Given the basin's economic importance and susceptibility to water scarcity, the findings underscore an urgent need for adaptive water management strategies to sustainably address future challenges.

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