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Detecting Land Use Change Impacts on Streamflow by Combining Field Data and Water Balance Modelling

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ABSTRACT

Over the last half-century, land use changes, including deforestation, urban sprawl, and open-pit surface mining, have accelerated across the Susurluk Basin in northwestern Türkiye. This study analysed how land use changes, damming and mining activities affected basin hydrology using empirical and analytical methods and the process-based Water Supply Stress Index Model (WaSSI). The monthly WaSSI water balance model was validated using streamflow data from gaging stations between 1980 and 2005. Two of the eight subbasins exhibited streamflow reductions of about 32%–42%, with mean annual discharge decreasing between 1980–1989 and 1990–2005, primarily due to land use change rather than climate variability. The runoff coefficient (Runoff/Precipitation) dropped from 22% during 1980–1989 to 12% during 1990–2005 in one rural subbasin containing several surface-mine ponds. Overall, empirical and process-based modelling indicated that land use dynamics, rather than climate, were responsible for the hydrological change. The monthly WaSSI showed satisfactory performance in subbasins with low human impacts (NSE > 0.50) but considerably lower performance (NSE < 0.20) in highly human-modified areas. This integrated study concludes that land use activities, especially pond creation for pit mining, were the dominant drivers of hydrological changes in the study area.

1 | Introduction

Climate and land use changes threaten the sustainability of water resources in Türkiye. The country has experienced a noticeable increase in temperature over the last four decades. This warming has resulted in frequent and severe extreme events like droughts (Bağçaci et al. 2021). Projections for the rest of the century indicate that temperatures will continue to rise, resulting in warmer conditions promoting evapotranspiration (Gorguner et al. 2019). Studies suggest that water and land management can also impact water resources (Davraz et al. 2019; Fujihara et al. 2008). Türkiye is a developing country with dynamic land use change (Çeler et al. 2023; Pamukcu et al. 2014). Over the past decades, basin-scale hydrologic processes have been strongly affected by urban growth and the conversion between forests and other land uses. The most common human activities influencing these changes are reservoir construction and mining. Mining activities are generally classified as open-pit or underground. Among them, open-pit mining has the most substantial environmental impact (Dontala et al. 2015). Many mining practices (e.g., perforation, blasting, transportation, and dumping) can impact the hydrologic system through changes in the land surface, such as clearing the original ecosystem, reshaping the slopes, and opening ponds. In Türkiye, open-pit mining for construction materials such as clay, soil, and rock is widespread, and these pits are visible across the country. According to Yıldız (2020), the forestlands allocated for mining reached 66,000 ha in Türkiye. After the mining activities are conducted, legislation requires that the land be rehabilitated and returned to its original use. However, ongoing mining may have impacts for decades (Yan et al. 2024). Although open-pit mining is one of the most widespread and impactful land use activities globally, its effects on watershed hydrology remain insufficiently studied (Santos et al. 2019; Tang et al. 2020).

The initiation or expansion of surface mining activities disturbs the landscapes, may deteriorate water quality, and alter hydrological processes (Chernos et al. 2022; López et al. 2020; Yang et al. 2023). Song et al. (2020) evaluated underground and surface mining and concluded that the latter reduced the streamflow significantly. However, several studies have shown that the hydrological response to mining can vary depending on local hydrogeological and climatic conditions (Bozan et al. 2022; Cui et al. 2025; Palash et al. 2025; Li et al. 2025). In arid and semi-arid regions, abandoned pits and excavation zones may enhance groundwater recharge and temporarily increase baseflow due to higher infiltration capacity (Evans et al. 2015; Chiew et al. 2018; Sun et al. 2020). Such contrasting findings indicate that open-pit mining impacts are not universally negative but highly site-specific. In the Susurluk Basin, extensive boron and lignite extraction in the upper subbasins may similarly modify infiltration-runoff dynamics by creating depressional areas and altering drainage pathways, emphasizing the need for basin-specific hydrological evaluation.

In addition to land use change, research on the combined effects of climate and land use change on streamflow has expanded rapidly in recent years (Hung et al. 2020). Guo et al. (2020) concluded that increasing imperviousness amplifies the influence of land use compared to climate change, making land use change a stronger driver of streamflow variation, especially in regions with extensive urbanization. Similarly, a meta-analysis by Chen et al. (2020) showed that land use change exerted a greater effect on streamflow than climate change in more than 60% of the reviewed case studies. The evaluated impact of land use activities on basin hydrology included afforestation, terracing, dam building, restoration, and grass planting. Overall, converting other land use types to forest practices had variable effects (Saha et al. 2019; Aguilos et al. 2021; Li et al. 2018; Yang et al. 2020).

The Marmara Region, located in the northwestern part of Türkiye, experienced rapid economic growth over the last half-century, resulting in dynamic land use changes and overuse of resources. The Susurluk Basin, one of the main basins in this region of Türkiye, experiences significant urbanization, population growth, and significant human impacts (Almas et al. 2022; Omwene et al. 2018). Boron and lignite ores are extracted through open-pit mining in the upper parts of the Susurluk Basin. The Bursa Plain of the Susurluk Basin is rich in under- and above-ground water supply compared to other regions of the country. However, since the beginning of the 2000s, water availability has come under pressure due to overpopulation, agriculture, and industrial developments (Ertürk 2011). Few studies have investigated the effects of land use change, particularly mining activities, on streamflow in this region.

This study aimed to identify the key drivers controlling streamflow variability in the Susurluk Basin over the past two to three decades. We assessed hydrologic changes using the Mann-Kendall (M-K) test and Double Mass Analysis (DMA), while the Elasticity Index (EI) was used to examine climate variability and climate change effects separately from other land use change influences. Groundwater well data were scrutinized with the Normalized Difference Vegetation Index (NDVI) to understand the influence of agricultural water withdrawals and land disturbance on flow dynamics. In addition, we combined field data and the Water Supply Stress Index Model (WaSSI) (Sun et al. 2011; Caldwell et al. 2012) to further distinguish the hydrological impacts of climate and land use changes. This integrated approach provides a framework for distinguishing climate- and land use-driven hydrological changes in developing basins. Unlike previous global applications of Budyko- or elasticity-based frameworks, this study integrates Türkiye's national land use data with NDVI and groundwater observations within a consistent hydrological attribution framework. This integration demonstrates how nationally reported land use datasets can be combined with auxiliary indicators to enhance the understanding of land use and climate interactions in basin-scale water assessments. The findings of this study can guide sustainable watershed management and planning in the Marmara Region and other basins facing similar human pressures.

2 | Materials and Methods

2.1 | Study Area—The Susurluk Basin

The Susurluk is one of the 25 main basins of Türkiye, located around the Marmara Sea in the northwest part of the country. This area has severe water scarcity and pollution due to intensive population and urbanization (Çiçek et al. 2023). The basin encompasses two major cities, Bursa and Balıkesir. Bursa is the largest urban area in the Susurluk Basin. The city underwent rapid urbanization due to immigration from the Balkans and various settlements in Türkiye attracted by intensive industrial activities in the city since the 1950s (Çalışkan and Hamarat 2011). The urban areas started to enlarge on one side, and the mining impacted the other side of the basin. The drainage area of the basin is about 23,750 km^2, and the elevation ranges from sea level to 2540 m (peak of Uludağ Mountain), with an average elevation of 640 m. The Susurluk Basin is a complex hydrologic system with five large tributaries (i.e., Kocaçay, Simav, Emet, Orhaneli, and Nilüfer streams) flowing in and out of two large lakes (Manyas and Uluabat lakes) and finally draining into the Marmara Sea (Figure 1).

The basin is dominated by forest (53.8%) and agricultural (30.6%) uses despite the expansion of urban areas in the north and west. From 1990 to 2015, both land uses reduced by 0.2% to 0.4% while reservoir areas more than doubled. The expansion of reservoirs was mostly in forestlands, croplands, and rangelands. The settlements increased 5.4% from 1990 to 2000 and 14.9% from 2000 to 2015. By 2015, the settlements had enlarged to 1.6% of the whole basin, while it was 1.3% in 1990.

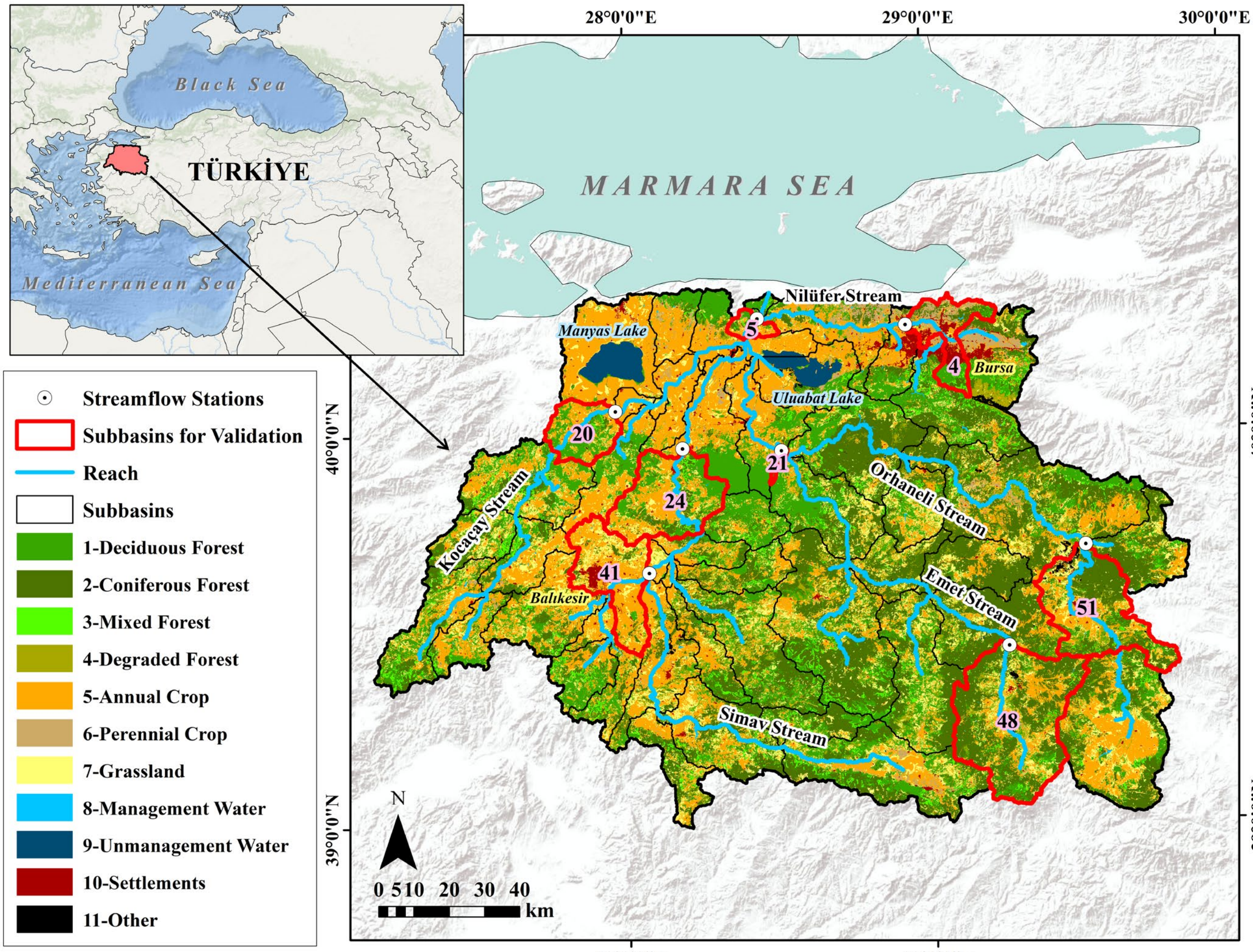

FIGURE 1 | Susurluk Basin location, boundaries of subbasins, mainstream branches, lakes, cities, and land use conditions (2015 land use data).

2.2 | Watershed Data

This study integrates field data and a water balance model to detect hydrological change and explore the cause of the detected changes.

There are several land use maps of the region going back to 1990, including the Coordination of Information on the Environment (CORINE) (https://land.copernicus.eu/en/products/corine-land-cover) and the ones developed by the government agencies (Çeler et al. 2023). In this study, we used the most recent and consistent database developed for the Greenhouse Gas (GHG) inventory purpose in 2019 in the framework of an EU-funded project titled "Technical assistance for developed analytical basis for the land use, land use change and forestry (LULUCF) sector". This land use tracking system can identify the land use changes annually from 1990 to 2015 with high accuracy and consistency with a precision of one hectare. This study is the first use of the tracking system beyond the GHG inventory submissions of Türkiye.

Several flow stations are present within the river network, but most have a short period of operation. Eight gauging stations were selected to validate the WaSSI model based on three main criteria: (i) continuous streamflow records of at least 20 years, (ii) spatial representation of different parts of the basin (headwater, midstream, and downstream subbasins), and (iii) data completeness without major gaps or inconsistencies. Stations with shorter or discontinuous records were excluded to ensure temporal consistency and reliability in model calibration and validation. While this selection may introduce some spatial bias toward well-monitored subbasins, it minimizes temporal uncertainty and improves the robustness of the hydrological assessment. The streamflow data was gathered from the State Hydraulic Works (DSI) database. The basin was divided into 61 subbasins to facilitate the intersection of flow stations and subbasin outlets. Although national land use data extend to 2015, the streamflow dataset was limited to 2005 due to the discontinuation of several gauging stations and restrictions on data access after that year.

The Susurluk Basin is dominated by forest and irrigated agricultural land uses. The villagers' water withdrawal from the creeks and groundwater is arbitrary and uncontrolled. The general practice is to pump creek water into the croplands with traditional irrigation. We used the Normalized Difference Vegetation Index (NDVI) (NCAR Staff 2023) time series produced by the Global Inventory Modelling and Mapping Studies (GIMMS) to detect changes in NDVI values that may indicate increases or decreases in irrigation over time.

TABLE 1 | Model input and auxiliary data, including sources, spatial resolution, and intended purposes.

Data type	Data	Source	Spatial resolution	Temporal resolution	Intended purpose(s)
Spatial model input data	DEM	SRTM	90 m	—	Subbasin delineation
	Soil	SoilGrids250 m 2.0	250 m	—	WaSSI Model parameters
	Land use	GeoVille	100 m	—	
	LAI	MODIS	500 m	8-day	
Meteorologic model input data	Precipitation	WorldClim 2.1	~21 km^2	Monthly	WaSSI model input, M-K test, DMA graph, EI calculation
	Temperature				WaSSI model input
Model validation data	Streamflow	DSI	—	Monthly	WaSSI model validation, M-K test, DMA graph, EI calculation
Auxiliary data	NDVI	GIMMS	~8 km	15-day	Irrigation detection
	Groundwater data	DSI	—	Yearly	Groundwater recharge estimation

We also examined groundwater withdrawal data provided by a recent study to better understand the groundwater dynamics of the Susurluk Basin (EuropeAid/134561/D/SER/TR 2015). The project compiled, identified, and analysed the data from the DSI, the national agency responsible for developing water resources in Türkiye. Groundwater resources are identified and monitored by the DSI through observation wells. The well data were evaluated in terms of regional withdrawal rates to determine the amount of water used and to assess whether the water table is declining. Table 1 provides a summary of model input data and auxiliary data, including their sources, resolution, and intended purposes of use. A flowchart provides study methodological details and input integrations (Figure 2).

2.3 | Flow Break Point Detections With Mann-Kendal Test and Double Mass Analysis

We used the Mann-Kendal (M-K) test and Double Mass Analysis (DMA) to detect the breakpoints of streamflow parameters. M-K is a widely used non-parametric test to detect the change point of hydrological data series (Zheng et al. 2016). Positive Zs values signify an upward trend, while negative values indicate a downward trend in the time series data. Trends are analysed at a specified significance level (α). For this study, a significance level of $\alpha = 0.05$ was utilized. When the absolute value of Zs is greater than the critical value $|Z_1\text{-}\alpha/2|$, the null hypothesis is rejected, indicating a significant trend in the time series. The critical value, $Z_1\text{-}\alpha/2$, is determined from the standard normal distribution table. At the 5% significance level, the null hypothesis of no trend is rejected if |Zs| exceeds 1.96.

DMA is a simple graphical method to evaluate the consistency of hydrological data. One variable's cumulative data is plotted against another's cumulative data. A break in the slope of a line represents a change in the relation between the variables (Li et al. 2018; Zheng et al. 2016).

2.4 | Elasticity Index (EI) Model for Attribution Analysis

We used the EI model to separate climate effects from the influence of land use, specifically the extension of open pit mines. In this method, we assumed that the variation in total streamflow is a combined effect of variations in climatic parameters (Q_{clim}) and land use changes (Q_{land}) (Equation 1)

$$d\,Q_{\text{tot}} = d\,Q_{\text{clim}} + d\,Q_{\text{land}} \tag{1}$$

In the EI method, the proportional change of streamflow is divided by the proportional change in a climate variable such as precipitation or PET (Gao et al. 2016; Hao et al. 2015; Zheng et al. 2016). We estimate the elasticity coefficients ε_1 for precipitation (mm/year) and ε_2 for potential evapotranspiration (mm/year) (Equation 2) for the first period (reference period) and predict the flow for the second period.

$$\frac{\Delta Qi}{Q_0} = \varepsilon_1 \frac{\Delta P_i}{P} + \varepsilon_2 \frac{\Delta E_{p(i)}}{E_p} \tag{2}$$

In Equation (2), Q_0 (mm/year), P (mm/year), and E_p (mm/year) refer to the mean annual Q, P, and E_p in the reference period, respectively. The predicted flow values were then compared with the observed values to reveal the cause of the difference, which, in our case, denote the influence of land cover change. We performed this analysis for Subbasins 48 and 51, and DMA revealed a significant change in streamflows.

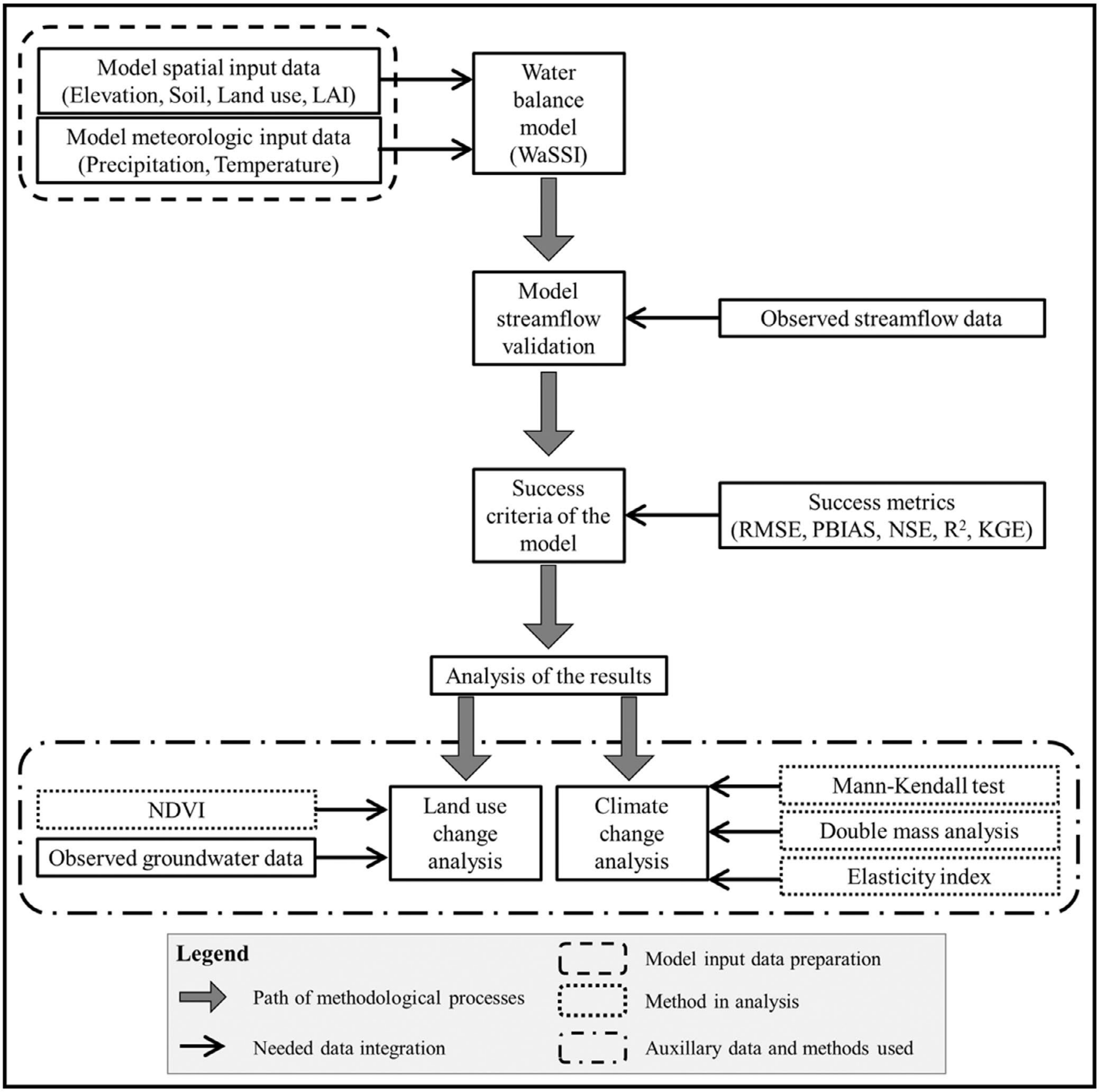

FIGURE 2 | Flowchart of methodological process and input integrations.

2.5 | Water Supply Stress Index (WaSSI) Model and Input Data

This study adopted the WaSSI model (Sun et al. 2011; Caldwell et al. 2012) because WaSSI provides an uncalibrated modelling solution on water balances with a low input data requirement. It calculated monthly water balance using leaf area, vegetation type, precipitation, and potential evapotranspiration (PET) to estimate actual evapotranspiration (AET), which also enabled estimation of monthly and annual runoff (Bagstad et al. 2018). The accuracy of the model has been evaluated at a monthly time scale at 72 United States Geological Survey (USGS) gauging stations (Sun et al. 2015) in China (Liu et al. 2013a, 2013b), and Rwanda (Bagstad et al. 2018). Previous WaSSI applications involved large-scale hydrologic assessments on the effects of droughts (Sun et al. 2015), forest thinning (Sun et al. 2015), urbanization (Li et al. 2020), and recently on climate change (Duarte et al. 2024) on key ecosystem fluxes. In this study, WaSSI was intentionally applied in its uncalibrated form to remain consistent with its original structure and to evaluate its transferability under data-limited conditions. Although model performance varied among subbasins, the analysis focused on reproducing relative trends rather than absolute discharge magnitudes.

In modelling the Susurluk Basin, we delineated 61 subbasins using the Shuttle Radar Topography Mission (SRTM) elevation data (Jarvis et al. 2008). Model input data are listed in

Table 1. WaSSI employed algorithms from the Sacramento Soil Moisture Accounting Model (SAC-SMA) (Burnash 1995) to compute infiltration, runoff, soil moisture, and baseflow processes corresponding to various land cover types within the basin. The soil parameters for the SAC-SMA model were derived from the global a priori 250 m parameters (Liu 2024), which are based on the SoilGrids250m 2.0 soil property dataset (https://soilgrids.org/). Essential data for estimating ET included remotely sensed monthly leaf area index (LAI), Hamon potential ET (PET) determined based on temperature and latitude (Hamon 1961), and precipitation. LAI data were prepared using MODIS products (Yuan et al. 2020). Monthly temperature and precipitation data were obtained from the WorldClim v2.1 (Fick and Hijmans 2017) historical dataset, which provides time-varying bias-corrected monthly surfaces at 1-km resolution rather than long-term climatological means. To verify the representativeness of the WorldClim data, we compared monthly and annual precipitation from WorldClim with station-based observations for eight gauging subbasins (1990–2005). The results showed strong correlations ($r = 0.85–0.88$) and consistent seasonal patterns across all subbasins, confirming that WorldClim adequately captures both interannual and seasonal variability in the basin.

3 | Results

To thoroughly assess the model's performance, we individually examined the land use dynamics of each of the eight subbasins. The modelled subbasins' land use and land use changes have been summarized below.

3.1 | Land Use Change

The Susurluk Basin includes 61 subbasins, with reliable long-term data from eight streamflow gage stations. Among these, Subbasins 4 and 5 are downstream, Subbasins 48 and 51 are upstream sections, and the other four (Subbasins 20, 21, 24, and 41) are in transition zones of the basin connecting upstream to the floodplain. Drainage area and land use percentages (year of 1990) of selected subbasins are given in Table 2.

Subbasin 4 has the highest proportion of urban land use and a pronounced elevation range, extending from mountainous zones above 2500 m down to sea level. Urban expansion initially replaced cropland between 1990 and 2000, and then mostly replaced forest areas after 2000, resulting in a slight overall decline in forest cover. Grasslands, perennial croplands, reservoirs, and degraded forests changed only marginally (< 1%). A high mountain with permanent snow cover lies at the headwaters, where temperature fluctuations affect snowmelt, and the presence of large water-bottling facilities further complicates the local hydrologic system. Situated where the Susurluk Basin discharges into the sea, Subbasin 5 showed stable land use conditions until 2000, after which croplands expanded at the expense of forests and grasslands. Subbasin 20 receives inflows from several upstream subbasins. Forest areas remained almost constant until 2000 but declined slightly afterwards due to the expansion of cropland and water bodies. The construction of the Manyas Hydroelectric Power Plant Dam on the upper segment of the main channel between 1993 and 2001 altered the flow conditions to some extent. Subbasin 21 encompasses the confluence of the Emet and Orhaneli Streams, where open-pit mining activities occur in a dispersed pattern across the upper reaches. Upstream subbasins such as 48 and 51 host extensive mining operations that indirectly influence downstream hydrology. Subbasin 24 drains a large part of the Simav Stream, within which another validation subbasin (Subbasin 41) is located. The landscape is dominated by forest and agricultural land with minimal urban occupation. During the study period, afforestation and forest-restoration programs reclaimed degraded forests and grasslands, increasing overall forest cover. A small dam constructed on a tributary after 2000 and the presence of sand- and stone-extraction sites near the stream channel also contributed to local hydrological modifications. Located downstream of several subbasins, Subbasin 41 is heavily influenced by cropland expansion. The city of Balıkesir, situated downstream of Subbasin 41, exerts a major anthropogenic influence on land use dynamics. Streamflow is partially regulated by the Taşköy Dam, constructed upstream within Subbasin 41 between 1990 and 2000, and the city has progressively expanded toward adjacent grasslands. Subbasin 48, as a headwater basin, its land cover remained relatively intact during the 1990s, yet about 53 km^2 of forest and 17 km^2 of grasslands were cleared for open-pit mining

TABLE 2 | The drainage area and land use percentages of selected subbasins.

Subbasin number	Drainage area (km^2)	Land use (%)					
		Forest	Crop	Grass	Water	Urban	Other
4	1290.2	62.20	23.20	5.80	0.30	7.20	1.30
5	21721.5	54.10	30.40	13.10	1.40	0.80	0.20
20	2281.9	49.40	34.80	15.00	0.10	0.60	0.10
21	9658.7	68.00	18.00	13.10	0.10	0.50	0.30
24	6450.9	51.40	32.20	14.90	0.20	1.10	0.20
41	1608.1	32.60	47.90	16.70	0.00	2.60	0.20
48	1163.3	66.60	20.00	12.80	0.00	0.40	0.20
51	1799.3	53.70	30.00	14.60	0.20	0.90	0.60

in the early 2000s. Expansion of the Hisarcık and Emet boron mines along the Emet branch created artificial ponds and excavation zones, altering the local terrain and surface-runoff pathways. Subbasin 51 is also located in the headwaters and has experienced extensive land-cover conversion associated with open-pit mining. Approximately 2862 ha of forest were lost during the 1990s, and a total of 94 km^2 was transformed into mining areas over the full study period, mainly replacing forests, annual croplands, and grasslands. The post-1990 expansion of the Tunçbilek lignite mine generated numerous artificial ponds and excavation areas, considerably modifying the natural landscape.

3.2 | Hydrologic Model Results

We applied the WaSSI model to the eight subbasins with reliable long-term streamflow data and integrated the results with empirical model time series analyses. The precipitation-runoff relation and land use rates of the drainage areas of the subbasins used for validation from 1980 to 2005 are given in Table 3. The annual precipitation ranged from 620 to 720 mm from the basin outlet to the headwater. Subbasin 4 had the highest runoff coefficient with the highest rate of urban land use. Other subbasins had urban areas of less than 10%. Forest and cropland cover dominate the subbasins and have a long-term average runoff coefficient of 0.29. Among the subbasins, Subbasins 48 and 51 were large headwater watersheds covered by around 50% forest cover and 30%–40% by croplands and grasslands.

WaSSI provided simulations without the need for calibration. Validating model streamflow predictions was necessary through the use of observational data. We applied the WaSSI model to the subbasins for validation and evaluated its accuracy using multiple statistical metrics. Because hydrologic models generate time series rather than single values, performance assessment requires temporal comparisons (Jackson et al. 2019; Althoff and Rodrigues 2021). Commonly used indices include the Nash–Sutcliffe Efficiency (NSE; Nash and Sutcliffe 1970) and the Kling–Gupta Efficiency (KGE; Gupta et al. 2009). While NSE accounts for both bias and variability, it is highly sensitive to peak flows, whereas KGE provides a more balanced assessment across flow conditions. Therefore, additional criteria such as the Coefficient of Determination (R^2), Percent Bias (PBIAS), and Root Mean Square Error (RMSE) were also employed to obtain a comprehensive evaluation. Table 4 shows the WaSSI model validation performance results.

The graphs of observed and simulated monthly and annual flows for individual subbasins are examined. We also provided the Double Mass Analysis (DMA) and Mann-Kendall (M-K) test results to reveal any change points in the time series (Figures 3–10).

For Subbasin 4, the WaSSI model predicted the timing of the storms, but there was a considerable difference in peak and total flow for individual events. The difference was more apparent on the monthly scale reaching hundreds of millimetres (Figure 3a). The simulation on an annual scale with global climate data underestimated the flow systematically (Figure 3b). To better look at the precipitation-runoff process, we also used local climate data in Subbasin 4, which is considered 10% impervious in urban land use. This improved the model performance, raising the monthly NSE value above 0.40. The rainfall-runoff linkage seems loose in Subbasin 4 because the streamflow inputs and outputs are unclear while passing through the urban city center. The DMA indicated a slight change in precipitation and streamflow responses in the early years but not a substantial change (Figure 3c). The precipitation-streamflow (P-Q) series and DMA indicated a change point in the 1980s followed by a straight line. There were no further significant change points in the flow series after 1984.

Among the model performance analysis for selected subbasin outlets, Subbasin 5 exhibited the most favourable match in observed and predicted streamflows. The quantity and timing of peak flows in hydrographs within Subbasin 5 are notably satisfactory (Figure 4a,b). When the P-Q series in Figure 4c is examined, two breakpoints in 1987 and 1995 are visible. Identifying any particular land use activities that correspond to these years is impossible since Subbasin 5 is downstream of several subbasins.

For Subbasin 20, the general WaSSI model performance was good but with predicted flows less responsive than the observed flows

TABLE 3 | Measured precipitation and streamflow of the subbasins used for WaSSI model validation.

Subbasin number[a]	Precipitation, *P* (mm/year)	Streamflow, *Q* (mm/year)	Runoff coefficient, *Q*/*P*
4	654	327	0.51
5	645	153	0.24
20	686	242	0.35
21	617	147	0.24
24	647	181	0.28
41	645	179	0.28
48	717	145	0.20
51	634	98	0.16
Average	652	188	0.29

[a]The subbasin number can be found in Figure 1.

TABLE 4 | The WaSSI model validation performance parameters for monthly and annual runs.

	Performance metrics									
	Monthly					Annual				
Subbasin number[a]	**RMSE**	**PBIAS**	**NSE**	R^2	**KGE**	**RMSE**	**PBIAS**	**NSE**	R^2	**KGE**
4	19.64	25.50	0.17	0.34	0.46	121.42	25.50	−1.40	0.13	0.32
5	6.71	15.70	0.73	0.79	0.79	44.47	15.70	0.53	0.78	0.71
20	20.90	−19.60	0.55	0.62	0.48	89.78	−19.60	0.25	0.50	0.63
21	7.25	18.60	0.65	0.72	0.76	55.47	18.60	0.02	0.56	0.57
24	10.44	−1.70	0.71	0.72	0.72	48.08	−1.70	0.66	0.69	0.83
41	12.15	−4.10	0.64	0.64	0.68	52.13	−4.10	0.64	0.70	0.81
48	11.97	57.70	0.00	0.66	0.29	102.85	57.70	−1.51	0.54	0.28
51	10.85	78.70	−0.79	0.49	0.02	96.78	78.70	−2.56	0.37	0.03

[a]The subbasin number can be found in Figure 1.

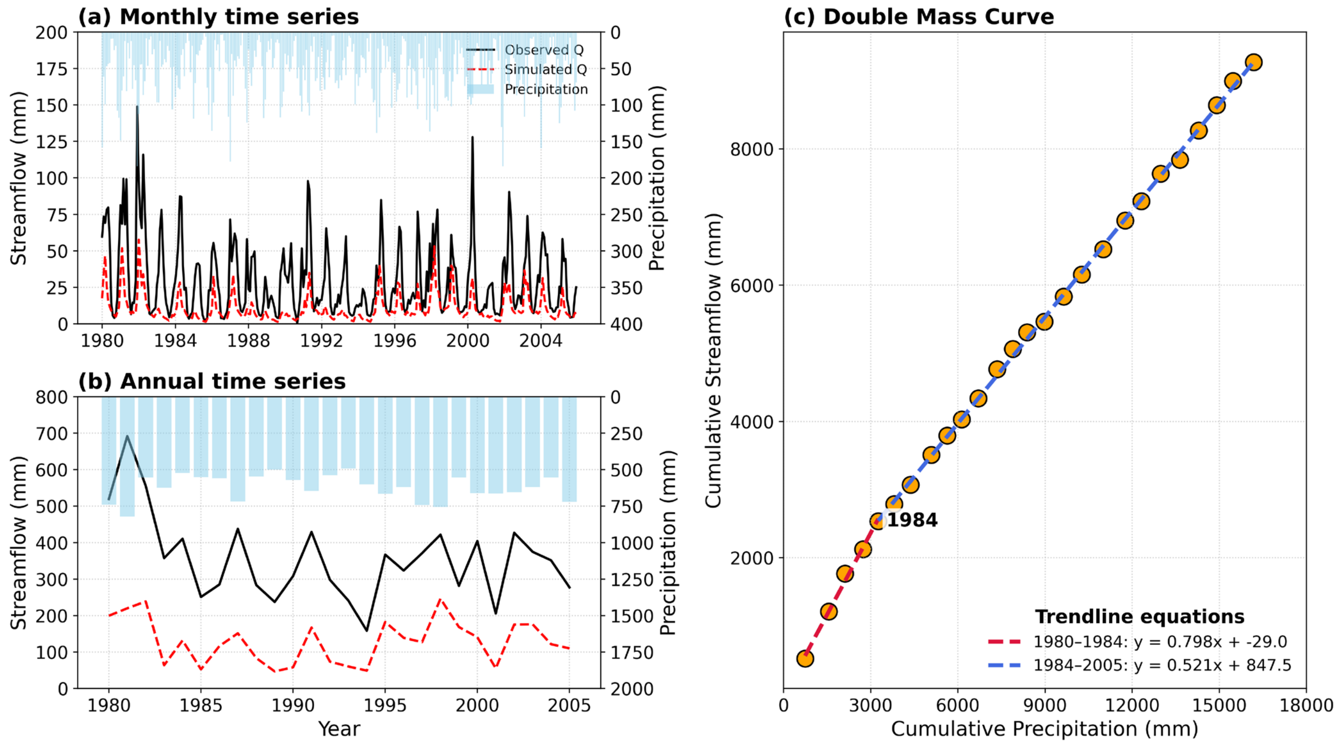

FIGURE 3 | WaSSI model (a) monthly, (b) yearly simulation results, and (c) DMA for Subbasin 4.

in catching up the peaks in monthly simulation (Figure 5a). The drainage area of Subbasin 20 is a forest and cropland-dominated lowland basin with a higher runoff coefficient than other subbasins. Deforestation occurred after the 1990s to construct a dam at the upper section of Subbasin 20. The observed flows dropped below predicted levels in 1995. The year 1993 had the most significant difference between observed and predicted flows. It was also the year that dam construction started. However, monthly and annual hydrographs (Figure 5a,b) did not indicate any long-term changes or break points in streamflow response to precipitation during the validation period. This situation has also been verified with the DMA (Figure 5c) and M-K test (|Zs| < 1.96 at 5% significance level).

Subbasin 21 is downstream of several subbasins, including Subbasin 48 and 51. The monthly WaSSI model performance is good (monthly NSE = 0.65) for the outlet of Subbasin 21, but there is still the issue of model underestimation for most of the simulation period (Figure 6a). The annual hydrographs revealed that the observed flow was higher than predicted until 1988 when the difference diminished, but the observed flow was still high; the observed vs. predicted flow values became very close after 1994 (Figure 6b). The *P-Q* series and DM graphs, identical to Subbasin 48 and 51, have a change point in the late 1980s. The *P-Q* trendline indicates a decreasing trend, but the M-K test resulted in a Zs value of −1.83, slightly lower than the 5% threshold. Consequently, there is not a statistically significant trend

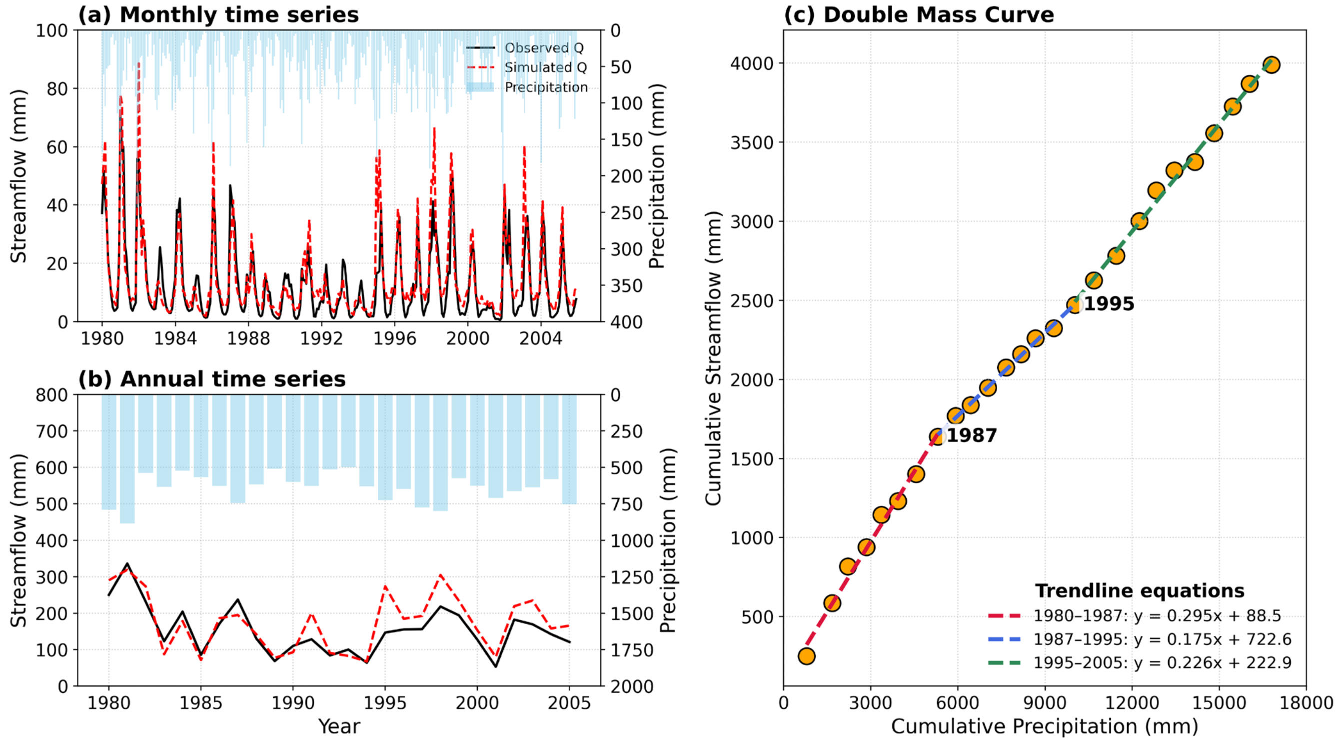

FIGURE 4 | WASSI model (a) monthly, (b) yearly simulation results, and (c) DMA for Subbasin 5.

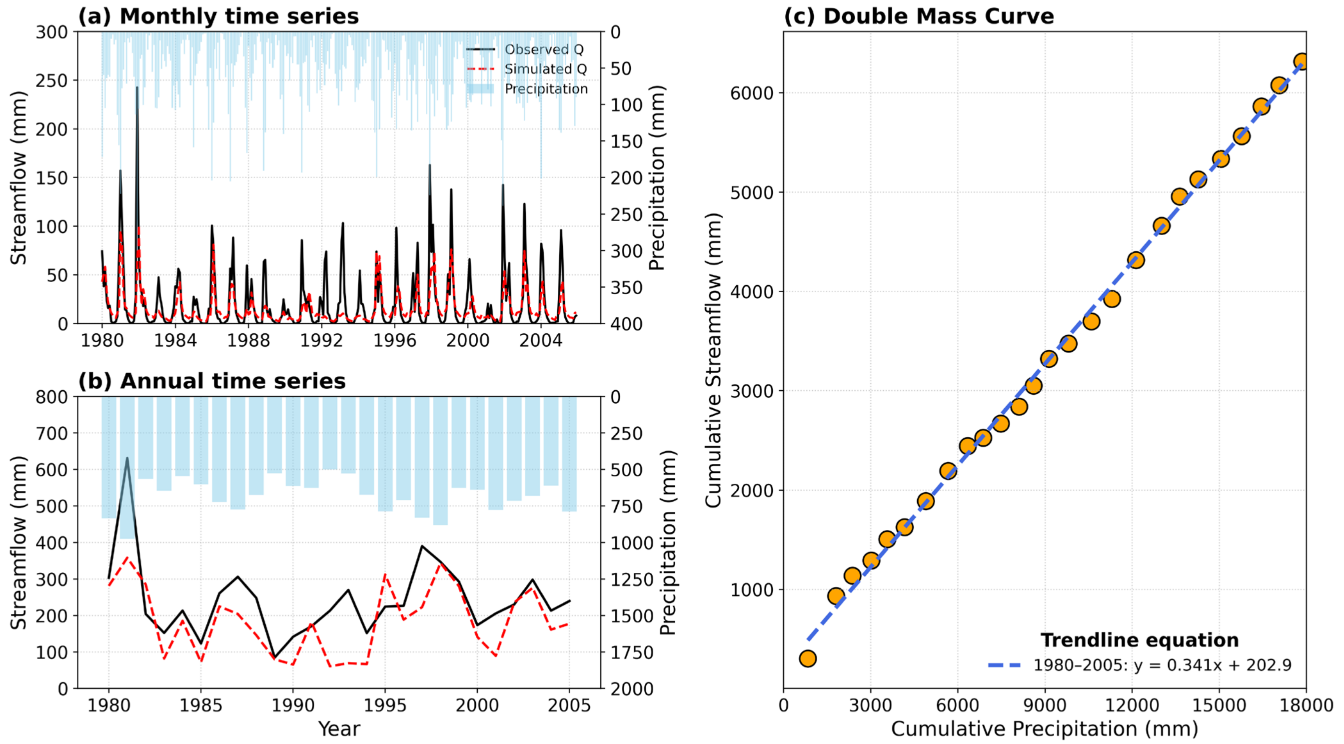

FIGURE 5 | WaSSI model (a) monthly, (b) yearly simulation results, and (c) DMA for Subbasin 20.

in the *P*-*Q* series but a change point due to upstream subbasins (Figure 6c).

For Subbasin 24, the WaSSI simulation results are very similar to those of Subbasins 20 and 21, as seen in the monthly and annual graphs (Figure 7a,b). The DM graph is also very similar to Subbasin 21. The drainage area of Subbasin 24 is much larger than that of Subbasin 21 and has been subject to land use changes. The significant land use change between 1990 and 2015 included 120 km^2 of afforestation. Some of the activities

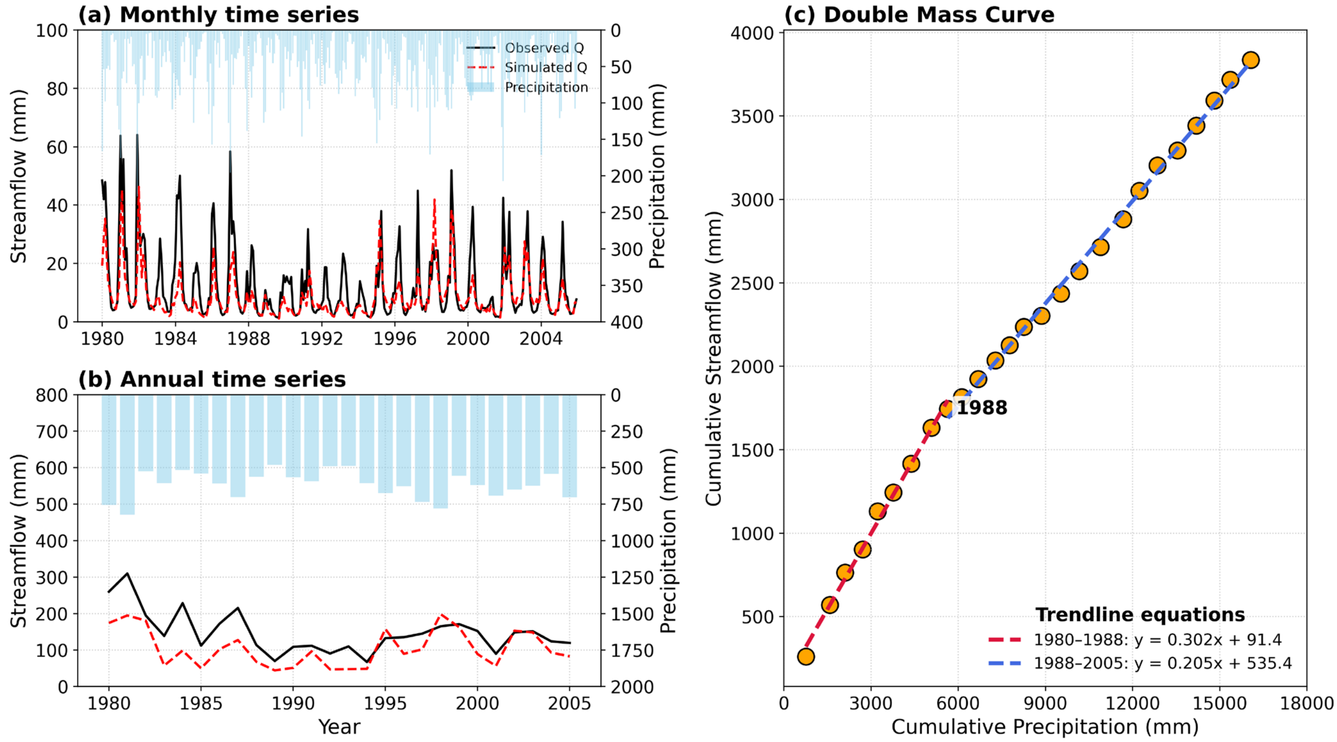

FIGURE 6 | WaSSI model (a) monthly, (b) yearly simulation results, and (c) DMA for Subbasin 21.

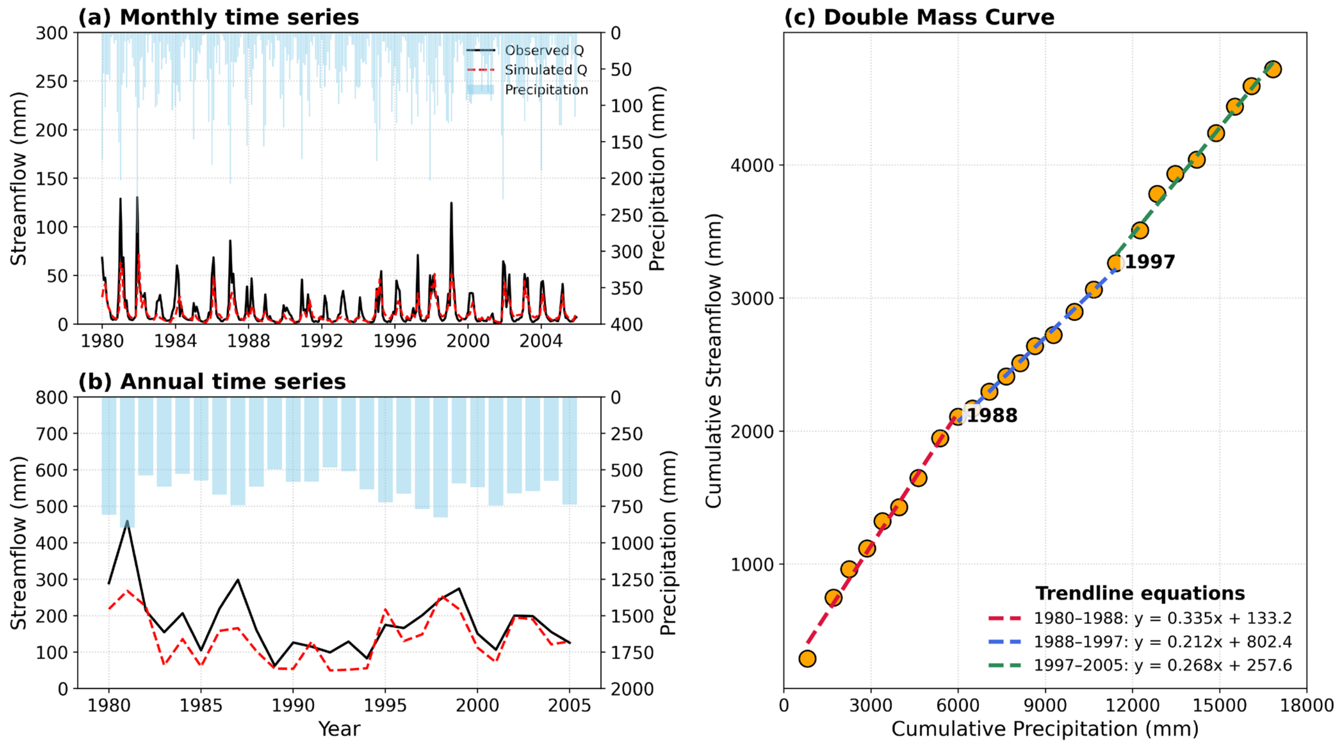

FIGURE 7 | WaSSI model (a) monthly, (b) yearly simulation results, and (c) DMA for Subbasin 24.

that may potentially affect the watershed's hydrologic response include adding a small reservoir and some sand/stone extraction pits around the stream channel after 2000. The observed flow of Subbasin 24 was over the predicted amount until 1991. It has been very close to the predicted flow after that year, with some years over the predicted. The M-K test did not result in a statistically significant decrease in the Q/P ratio for the assessment period (Zs = −1.03: $p < 0.05$), but the change points identified by the DMA were similar to Subbasin 21 (Figure 7c).

The WaSSI model performance for the Subbasin 41 was quite good (monthly NSE = 0.64). The M-K test did not indicate any

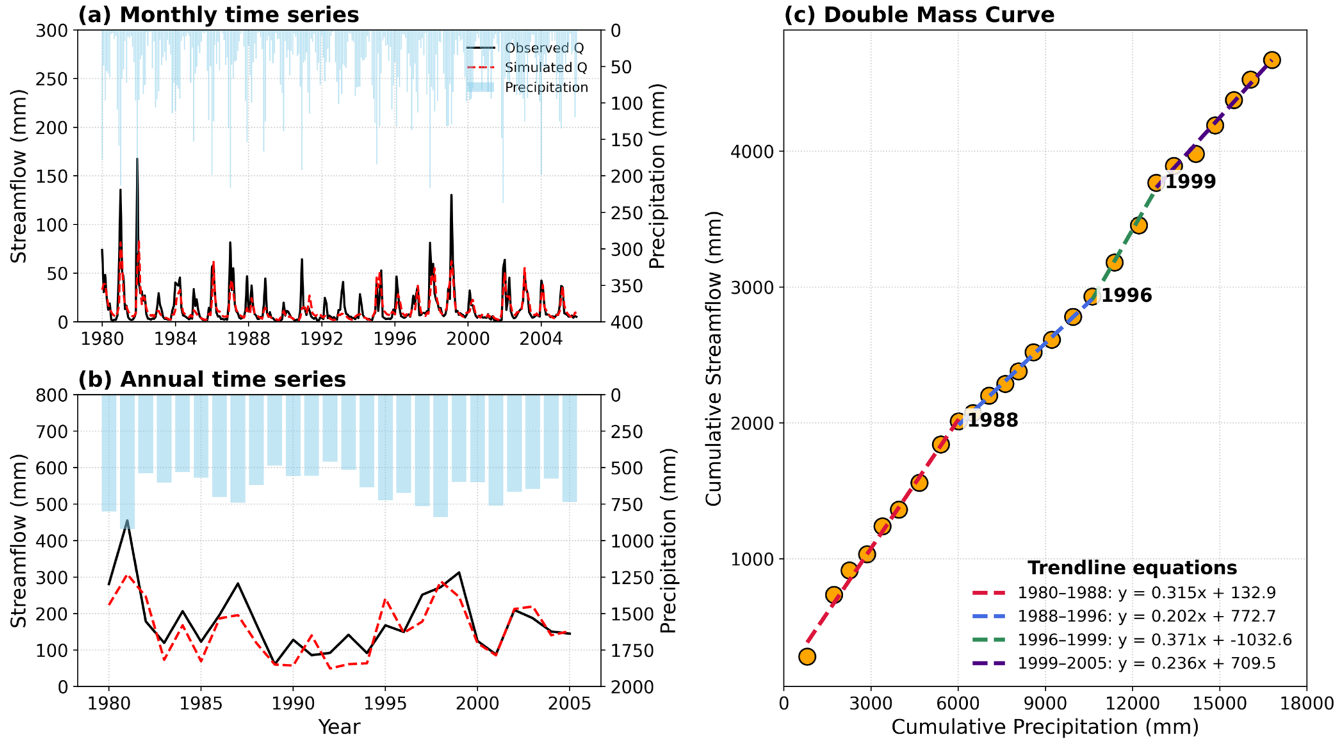

FIGURE 8 | WaSSI model (a) monthly, (b) yearly simulation results, and (c) DMA for Subbasin 41.

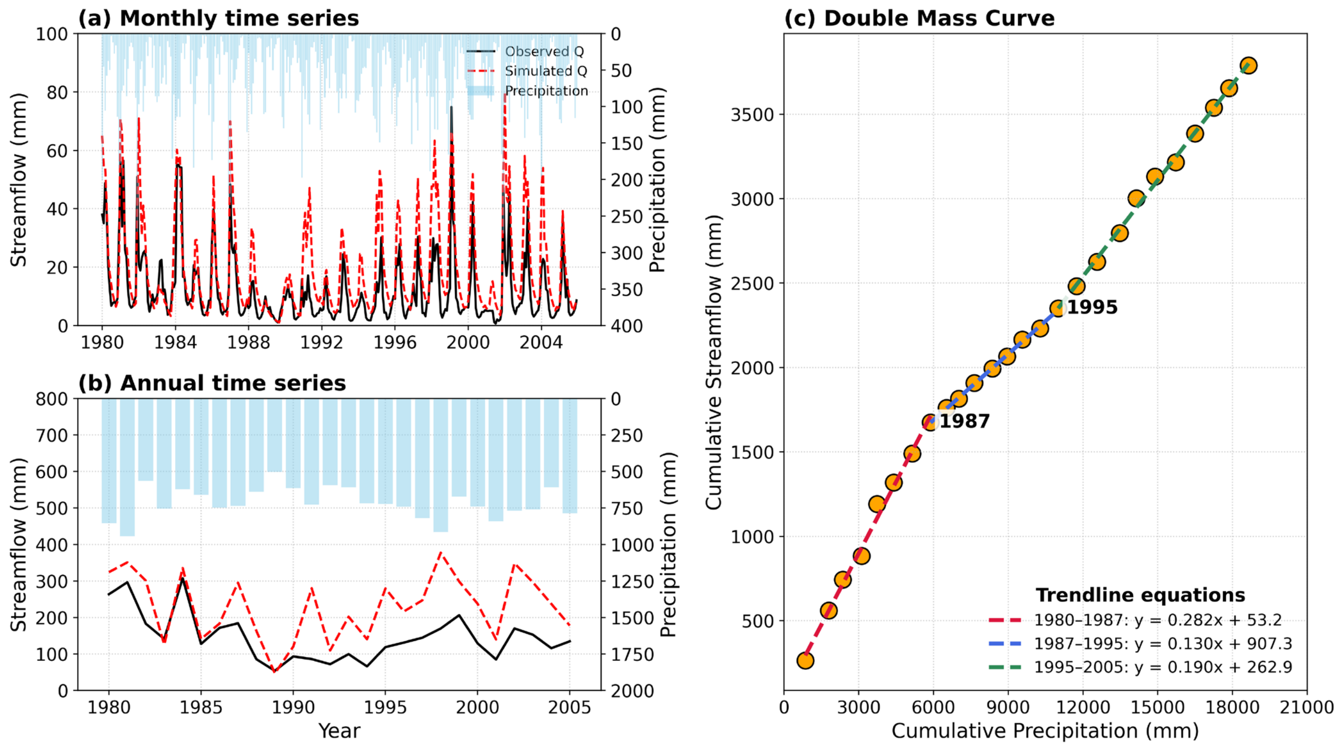

FIGURE 9 | WaSSI model (a) monthly, (b) yearly simulation results, and (c) DMA for Subbasin 48.

trend (Zs = −1.34) in the *P-Q* series. However, a few change points were identified by the DMA. Upstream subbasins of 46 and 53 may cause this. Also, a dam was constructed between 1990 and 2000 (Figure 8).

The validation results of Subbasins 48 and 51 have similarities. At a monthly scale, for Subbasin 48, the timing of the peaks fits well, but the simulated flows fail to catch the observed values during the rest of the time series except for a couple of years

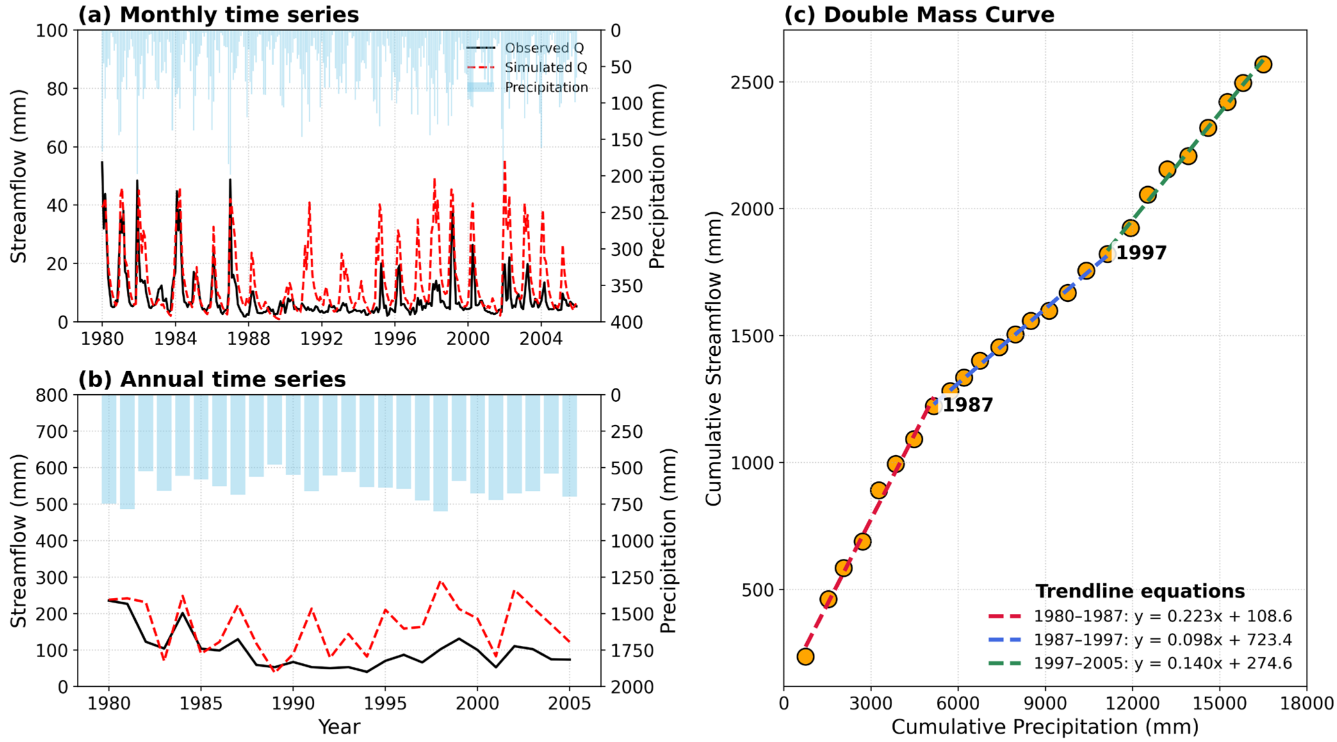

FIGURE 10 | WaSSI model (a) monthly, (b) yearly simulation results, and (c) DMA for Subbasin 51.

(i.e., 1999 and 2005, Figure 9a). The observed flow series seems less responsive to the precipitation for both high and low flow sequences. In the annual comparison of observed vs. predicted flow values, the streamflow response seems low after 1990 (Figure 9b). The M-K tests for the Q/P ratio of these two subbasins had decreasing trendlines like other subbasins, but the series for Subbasin 51 had a statistically significant (Zs = −2.13) decreasing trend. The trend for Subbasin 48 was not statistically significant (Zs = −1.3) according to the M-K test. According to the DMA, the cumulative P-Q series breaks in 1988, first with a decline in streamflow. The second breakpoint corresponds to 1996 as the streamflow increases but not with the same slope as before 1989. This kind of change in the P-Q graph suggests a change in the hydrologic response of the subbasin to the precipitation that can be caused by land use change or changes in land use practices (Figure 9c).

For Subbasin 51, the break year for the series break is 1989, according to the DM graph. Like Subbasin 48, the observed flow series of Subbasin 51 went on around 50% below the predicted flow series after the 1990s. The average runoff coefficient (Runoff/Precipitation) dropped from 22% in 1980–1989 to 12% between 1990 and 2005. The slope of the DM graph changed again in 1998, similar to that of Subbasin 48 (Figure 10).

Using local climate data to improve model performance in Subbasin 4 was somewhat effective. However, for Subbasins 48 and 51, model performance did not improve even with the incorporation of local climate data. This suggests that land use differences in these subbasins were independent of climate inputs and played a dominant role in influencing streamflow and limiting model performance. In contrast to the other subbasins, the presence of open-pit mining activities in Subbasins 48 and 51 may have contributed to these effects.

3.3 | Elasticity Index Model Results

Since both subbasins had change points around 1989, we applied the EI to identify the drivers of streamflow reduction. Such changes in streamflow may occur because of periodic climatic anomalies or human impacts such as land use changes. In our case, we wanted to eliminate the impact of climate on this change by using EI. For subbasins 48 and 51, we split the data into the pre-change period (T_0: 1980–1989) and the post-change period (T_1: 1990–2005). Using annual precipitation and PET data, we estimated the ε_1 and ε_2 coefficients for Subbasin 48 for the reference period (T_0) as 0.26 and zero, respectively. The r^2 of the regression equation ($Q_0 = 0.81688 + 0.260865\ P_0$) was 0.80 ($p < 0.001$). The ε_1 and ε_2 coefficients we estimated were 0.54 and −0.40 for Subbasin 51. The r^2 of the regression equation ($Q_0 = 4.898189 + 0.539426\ P_0 - 0.397034\ \text{PET}$) was 0.84 ($p < 0.001$). The predicted Q series for T_1 for the watersheds were then compared with the observed Q data of the 1990–2005 period to reveal the influence of land use.

In Subbasin 48, the estimated difference between the predicted and observed series was a significant ($p < 0.01$) −67 mm flow reduction per year from 1990 to 2005. The mean flow was reduced to 123.4 mm/year. In this period as compared to the 181.5 mm for the 1980 to 89 reference period ($p < 0.0.1$). However, the actual flow reduction between the two periods remained at 58.1 mm/year. As the increased mean annual precipitation and change in PET offset the difference by 8.9 mm/year. Compared to what was predicted, the share of LULC in flow reduction in the 1990 to 2005 period was −54.3%.

In Subbasin 51, the trends of observed and predicted flows were almost identical. The estimated difference between the predicted and observed series was −63.6 mm/year. Flow reduction for the

TABLE 5 | Impacts of land use and climate change on streamflow for Watershed 48 and 51 as detected by the Climate Elasticity Method.

Subbasin number	Water balance component (mm/year)	Period 1 (1980–1989)	Period 2 (1990–2005)	Difference between Period 1 and Period 2	Impact of LUC (%)	Impact of CC (%)
48	PET (WaSSI)	540.9	553.5	12.6		
	Precipitation (P)	702.1	726.8	24.7		
	Flow (Q)	181.5	123.4	−58.1	86.7	13.3
51	PET (WaSSI)	520	532.5	12.5		
	Precipitation (P)	619.9	643.5	23.6		
	Flow (Q)	133.5	77.2	−56.3	88.5	11.5

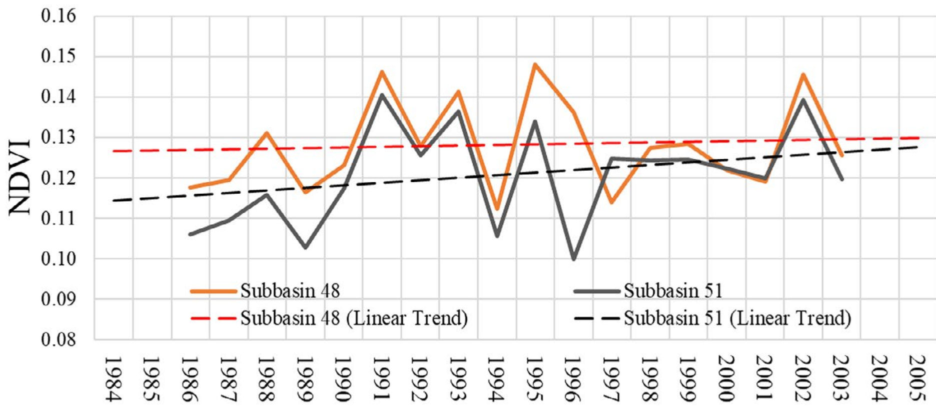

FIGURE 11 | Annual change in NDVI values of croplands in Subbasin 48 and 51.

1990 to 2005 period. The mean flow reduced to 77.2 mm/year. In this period compared to the 133.5 mm/year. For the 1980 to 89 reference period. Again, the actual flow reduction between the two periods remained at 56.3 mm/year. As the increased mean annual precipitation and change in PET offset the difference by 7.3 mm/year. (Table 5). When the influence of climatic variability is eliminated with the method, the share of LULC in flow reduction in the 1990 to 2005 period, compared to predicted, becomes −82.4%.

The EI approach revealed that the water yields of both headwater subbasins were significantly ($p < 0.01$) reduced for the period after 1989, and the reason for this reduction was not the changes in precipitation or PET. The major LULC in these subbasins was open pit mining, as described in the 3.1. Land Use Change section.

3.4 | NDVI and Groundwater Analyses

We established an NDVI time series for croplands in Subbasins 48 and 51 to reveal any vegetative intensification due to increased irrigation. Both subbasins exhibited slight but statistically insignificant upward NDVI trends (Subbasin 48: +0.00054 year.$^{-1}$, $p = 0.07$; Subbasin 51: +0.00046 year.$^{-1}$, $p = 0.09$), indicating no meaningful long-term vegetation change (Figure 11). The low slopes and p-values close to the 0.1 threshold suggest minor greening tendencies without statistical confidence. Overall, the results imply that large-scale irrigation expansion or vegetation-driven evapotranspiration increase is unlikely to have influenced streamflow during the analysed period.

The groundwater data also confirmed that there is no evidence of overexploitation of aquifers in the basin (Table 6). Eight groundwater systems were evaluated using recharge, withdrawal, and existing resource data obtained from DSI. All groundwater sources exhibited withdrawal-to-recharge ratios below 1, indicating stable groundwater conditions. The highest ratio (0.9) was observed around the Manyas and Uluabat Lakes, followed by the Nilüfer aquifer (0.7), which lies beneath Subbasin 4 and represents one of the largest groundwater reserves in the basin. In contrast, the Domaniç and Balıkesir Kuzeyi aquifers had low ratios (< 0.4), suggesting sustainable withdrawal levels.

To assess spatial variability, the withdrawal/recharge ratios were compared across the eight subbasins, showing values ranging from 0.1 to 0.9 with a mean of 0.5. These results indicate that groundwater use is generally balanced, with localized stress only in the downstream areas. Although long-term temporal records were not available to perform formal trend testing, the spatial comparison provides a preliminary understanding of groundwater pressure distribution.

4 | Discussion

Streamflow in a watershed is affected by multiple factors (Hou et al. 2023), but lasting changes usually result from long-term or permanent disturbances. In this study, we validated a hydrological model to assess land use effects on streamflow, analysing each subbasin individually due to their differing hydrologic

TABLE 6 | Groundwater resources of Susurluk Basin concerning the validated subbasins.

Groundwater subbasin code	Name	Recharge rate (hm^3/year)	Average withdrawal rate (hm^3/year)	Existing resource (hm^3/year)	Withdrawal/Recharge	Surface subbasin number
TR03YAS01003	Tavşanlı	9.8	2.9	6.9	0.4	51
TR03YAS01004	Domaniç	13.6	2.4	9.6	0.3	51
TR03YAS02001	Emet	17.5	7.85	12.3	0.6	48
TR03YAS04001	Nilufer	364.6	179	255.2	0.7	4
TR03YAS05002	Balıkesir Bigadiç Kepsut	96.1	52.8	76.9	0.7	41
TR03YAS05003	Balıkesir Kuzeyi	11.5	2.5	8.1	0.3	24
TR03YAS06001	Manyas-Uluabat	201.8	125.1	141.3	0.9	5, 20, 21, 24
TR03YAS06002	Manyas Mermer	40.3	1.9	32.3	0.1	20

behaviour. All subbasins we used for validation had decreasing trendlines for the annual Q/P ratio series from 1980 to 2005. We analysed the climate parameters and land use, considering that the decreasing trends in the Q/P series could be caused by increasing temperatures and associated ET or long-term changes in land-based activities such as increased irrigation.

For each subbasin, change points were detected in the precipitation-runoff (P–Q) relationship. The results suggest that these changes may be partly driven by climate variability, with open-pit mining and associated human activities likely playing a more dominant role through their effects on water retention and evaporation. On the other hand, by using DMA, we also found that there were periods where Q/P values changed systematically, which were also on the side to decrease streamflow response. We looked closely at the subbasins to identify the land use activities that may cause these change points. Consequently, we found that open pit mining activities corresponded to the dates of change points in Subbasin 48 and 51. Although detailed dam operation data were not incorporated into the model, the regulatory influence of major reservoirs such as the Çavdarhisar Dam was considered qualitatively. The dam may have contributed locally to the observed flow variability, but its overall effect is likely secondary compared to broader land use and climatic drivers. However, it should be noted that model performance in these subbasins was relatively weak, which limits the confidence in the quantitative interpretation. Therefore, our inference regarding the influence of mining activities is based on the convergence of multiple indicators (DMA, NDVI, and groundwater evidence) rather than on model predictions alone. We further verified this by applying the EI method since variations in climate parameters could also cause the changes. Zheng et al. (2016) applied the model to the Miyun Reservoir in Beijing to distinguish the relative influence of climate and land use change on streamflow variations. In our case, the mean streamflow of Subbasin 48 reduced (58.1 mm) by 32% during the 1990–2005 period as compared to the reference that is 1980–1989. According to the EI approach, the streamflow would reduce by 67.0 mm on average if the P and PET were identical to the reference period. Therefore, the influence of the change in climatic parameters was to compensate for a streamflow reduction of 8.9 mm on average. In other words, we would observe an increased streamflow for Subbasin 48 if the influence of land use was neutral. The situation was quite identical for Subbasin 51. An around 56.3 mm streamflow decrease for the 1990–2005 period compared to reference 1980–1989 would be 63.6 mm if the climate did not compensate for 7.3 mm. The influence of climatic parameters P and PET were 13% and 11% for Subbasin 48 and 51, respectively. The rest was assumed to be controlled by land use.

While open-pit mining has been widely investigated in terms of its environmental and pollution impacts, its hydrological consequences remain less understood. These impacts may occur over different temporal scales, ranging from short-term disturbances to long-term cumulative effects. Lehmkuhl and Stauch (2023) reported a catastrophic flooding event linked to an open-pit mine that caused severe erosion and sedimentation within hours. Over longer periods, Chernos et al. (2022) showed that open-pit coal mining can alter streamflow and water quality. They noted that mining operations in headwater catchments may significantly modify flow regimes through water storage, settling ponds, and delayed water release. These processes are potentially relevant to the Susurluk Basin. In line with these observations, our study considered both land use change associated with open-pit mining and climate variability as key factors influencing streamflow response. Although data limitations prevent definitive attribution, our analyses suggest that open-pit mining activities may play a considerable role alongside climatic variability in shaping the long-term hydrologic behaviour of the basin. These findings align with the historical developments in the region. The construction of the Çavdarhisar Dam between 1985 and 1990, for instance, likely initiated additional regulation of streamflow, as the reservoir, though situated on a tributary, would have begun retaining part of the river discharge from the early 1990s onward. Moreover, the expansion of the coal mine supplying the Tunçbilek thermic power plant, located near the outlet of Subbasin 51, appears to have intensified between 1990 and 2015, accompanied by the formation of several ponding areas. Such simultaneous developments in dam construction and open-pit mining may have collectively contributed to the altered flow regime and sediment dynamics observed in the basin. Urban expansion and smaller-scale hydraulic structures may have also played a role in modifying runoff generation and stream regulation, although their effects were not quantified within this study. In addition to mining, other land use–related processes such as localized irrigation and soil compaction from mining and construction activities may also have contributed to the observed changes in runoff generation and infiltration. These factors could influence surface–subsurface interactions, potentially reinforcing or offsetting the hydrologic impacts attributed to mining. Therefore, the interpretation of mining effects in this study reflects one of several interacting anthropogenic drivers rather than a single dominant cause.

These anthropogenic interventions also influenced the performance of hydrologic simulations. The eight gauging stations were selected to ensure spatial representativeness across the headwater, midstream, and downstream zones of the Susurluk Basin, while maintaining long and continuous streamflow data. Although this selection may introduce some spatial bias toward better-monitored areas, it provides consistent long-term observations necessary for reliable model validation. According to NSE and KGE values, Subbasins 4, 48, and 51 exhibited relatively lower performance, particularly at the annual scale. R^2 exceeded 0.5 in all cases except for the annual result of Subbasin 51. Higher RMSE values, such as in Subbasin 4, indicate poorer model accuracy, while PBIAS revealed underestimation in Subbasin 4 and overestimation in Subbasin 51. Overall, the WaSSI model performed well for most subbasins despite the lack of calibration. Only Subbasins 4, 48, and 51 exhibited weaker fits. Subbasin 4 is urban-dominated, whereas 48 and 51 are large upland catchments affected by decreasing streamflow trends, likely associated with mining and climatic shifts. To better interpret these hydrologic changes, complementary analyses, including the M-K test, DMA, and EI, were conducted. The M-K and DMA detected change points in precipitation and streamflow, while the EI revealed that the post-1989 decline in streamflow was primarily driven by land use alterations (parameter m) rather than increased evapotranspiration. Additionally, the groundwater table and NDVI change analyses supported these findings. The NDVI series and groundwater utilization data did not indicate any significant alteration in vegetation structure or cropping practices that could lead to enhanced water use in the long term (Lin et al. 2022).

5 | Conclusions

Land use and climate change are widely recognized as key factors influencing water resource dynamics. Understanding their relative importance is essential for developing adaptive and sustainable land use policies. Although climate change cannot be directly controlled, appropriate land management can support the long-term sustainability of watershed systems. In this study, we applied the WASSI model, supported by auxiliary analyses, to explore how land use and climate variability may have influenced streamflow patterns in the Susurluk Basin. The results revealed a decline in streamflow in several subbasins during the 1990s, which, within the limitations of this study—particularly the availability of data restricted to the 1980–2005 period—appears to be partly associated with land use changes related to the establishment and expansion of open-pit mines. Future studies should incorporate more recent hydrological observations to better represent the post-2005 period of mining expansion. Building on this, future research could also extend the framework to include climate change projections, allowing for a more comprehensive assessment of potential hydrologic responses under different land use and climatic conditions. These mining activities may have contributed to alterations in the basin's hydrological balance through the development of large retention ponds and landscape disturbance. While open-pit mining is often reported to affect surface and groundwater quality, our findings indicate that, under the conditions analysed here, it could also have a potential influence on streamflow quantity by modifying drainage and evaporation processes. In addition to mining, other anthropogenic factors such as dam regulation and urban expansion may also have contributed to the observed hydrologic alterations, although their effects were not explicitly quantified in this study.

Overall, the study achieved its objective of identifying the major factors controlling streamflow variability in the Susurluk Basin. By distinguishing the relative effects of climate variability and land use change, particularly those associated with open-pit mining, the results provide insight into the mechanisms shaping basin-scale hydrology in rapidly developing regions of Türkiye. These basin-scale insights may also support ongoing efforts to strengthen sustainable mining practices in Türkiye by highlighting the importance of monitoring cumulative hydrological impacts and integrating water-resource considerations into future land use and permitting processes. These findings contribute to a better understanding of human–environment interactions and may inform sustainable watershed and resource management strategies under ongoing climatic and land use pressures.

Author Contributions

Ning Liu: formal analysis, data curation. **Eren Dağra Sökmen:** data curation, software, formal analysis. **İsmail Bilal Peker:** data curation, software, formal analysis, methodology. **Yusuf Serengil:** writing – review and editing, methodology, conceptualization, writing – original draft, data curation, formal analysis. **Steven G. McNulty:** writing – review and editing, methodology, validation, formal analysis, software, data curation, supervision. **Sezar Gülbaz:** conceptualization, supervision. **Ge Sun:** data curation, supervision, formal analysis, software, methodology, validation, writing – review and editing.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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