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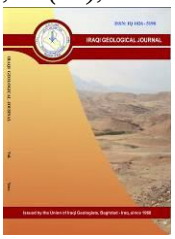

Application of SWAT Model to Assess Land Use-Land Cover Impact on the Hydrological System of Heshkaro River in Duhok City, Kurdistan Region, Iraq

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Abstract

The watershed analysis and assessment of the factors affecting the surface runoff is an utmost priority for successful catchment area management. Land use and land cover are among the most important factors affecting the hydrological response of the watershed. The Heshkaro River is one of the two main rivers crossing Duhok City. The methodology of this work included the investigation of temporal variations of land use and land cover maps for the Heshkaro River for the last three decades (1986–2022). The supervised classification style was applied to generate the land use and land cover maps for the different types of satellite images. The SWAT model was set up to construct the hydrologic model to simulate the stream flow of this river during the specified period. The thematic layers of land use-land cover, soil, DEM, and weather parameters were initialized for the model. The daily discharge of the river was measured in the field during the rainy period of 2022. The model designed was calibrated and verified for the daily field-measured runoff. The results of calibration and validation demonstrate a good match between the observed and simulated daily flows, according to the values of R2 of 0.92, Nash Sutcliff Efficiency of 0.91, and Root Mean Standard Deviation Ratio of 0.04 for calibration and R2 of 0.85, NSE of 0.90, and RSR of 0.01 for validation. The assessment impact of land use and land cover on the Heshkaro River demonstrated a significant effect of LU/LC classes on the hydrological process in the Heshkaro River basin. The outcome of this research will provide the requirements for successful management of the Heshkaro River watershed with a guarantee of the basin's environmental sustainability.

Keywords: Land use land cover; Remote sensing; GIS; SWAT model; Heshkaro river

1. Introduction

Hydrological models are essential in evaluating and simulating different water resource variables at the watershed scale and understanding their interactions with the management and planning of water resources. Where human interference (increasing global population, industrialization, land-use change), climate change, floods, and droughts have become more frequent and are the major concerns for sustainable development worldwide. Therefore, water resources management is inevitable for the sustainable development of human society (Dakhlalla and Parajuli, 2019; Salih and Khattab, 2023).

The change in Land use and land cover (LU/LC) is one of the factors that directly affect the watershed hydrological system, quantity, and quality (Oo et al., 2020). It significantly reduces overland

flows due to its impact on evaporation, transpiration, temperature, precipitation, surface runoff potential, and decreases in groundwater recharge and soil infiltration capacity of the catchment area, and the absorption of solar radiation (Kassa and Forech, 2009; Cooper, 2010). Furthermore, monitoring LU/LC changes is important for determining the potential effects on the ecosystem. This often leads to various environmental influences, such as soil erosion, soil moisture, soil nutrients, changes in local climate, etc. These effects not only impact the watershed boundaries but also lead to many adverse effects downstream (Thakur et al., 2016). The study of watersheds can give concrete evidence of the effects of LU/LC change on runoff (Tan et al., 2022). Because of these factors, hydrological models are becoming increasingly crucial for researching how LU/LC change affects the hydrological cycle in the environment (Getu Engida et al., 2021). Several studies were conducted on the hydrology of the watershed using LU/LC data in various regions of the world using the Soil and Water Assessment Tool (SWAT), such as Al-Khafaji et al. (2017) and Kassem et al. (2020).

SWAT is a useful hydrological modeling tool for simulating the impacts of watershed processes and water management strategies on the water cycle. It is an open-source tool used worldwide and in many watersheds to understand the ecological processes driven by hydrology. Recently, the SWAT model has become more popular because it is particularly effective at addressing several hydrology-related challenges (Izydorczyk et al., 2019).

The Heshkaro River basin is one of the most important basins in Duhok City and has been affected by changes in land use/ land cover in a way that may threaten citizens' property as well as significant environmental risks. Therefore, all the previous advantages and challenges mean the SWAT model's application to simulate the hydrological behavior of Heshkaro is urgent. This application has become more fruitful with integrating Remote sensing and GIS in the SWAT environment work. The aims of the study are 1) Application of the SWAT Model to simulate the hydrogeological system of the Heshkaro River watershed by suiting the modeling framework simulation for the year 2022. 2) Assess the impact of LU/LC changes over time on the hydrogeological system of the Heshkaro River watershed through the SWAT model.

The study provides scientifically validated insights that can guide sustainable watershed management and climate adaptation strategies.

2. Materials and Methods

2.1. Study Area

The Heshkaro River is one of the two main rivers crossing Duhok City, starting from the north and east of the city (Fig. 1). This river originates from a place close to the Bade Village in the north and heads south, where it unites with the Duhok River in the far southwest of the city. This river crosses the urban area in the southern part (Goran and Khattab, 2023). Geographically, it is located between Latitude 36° 47' 30" and 36° 56' 30" N and longitude 42° 58' 30" and 43° 10' 30" E. The climatic conditions of the area are similar to the Mediterranean climate conditions (Bleej, 2020). The Mediterranean climate is distinguished by dry summers and a moderate amount of precipitation in winter (Mzuri et al., 2021). Moreover, it is often accompanied by snow due to the presence of mountain ranges. The rainy season typically starts in mid-October and ends in early May. The month with the most precipitation in the area occurs in January.

Topographically, the Heshkaro River basin is bounded by two high mountains from the north and south, Bekhair and Duhok, respectively. The elevation of the study area ranges from 529 to 1350 m above sea level. Geologically, the study area is located within the High-Folded Zone in the Outer Platform's Western Zagros Fold Thrust Belt (WZFTB), according to the tectonic division of Iraq It covers the ages from Late Turonian to Danian, Middle Paleocene to Eocene, and late Eocene to Recent,

and includes outcrops from the Late Cretaceous to the Pliocene (Jassim and Goff, 2006; Bamerni et al., 2021). The rock units exposed in the study area, from the oldest deposits to recent, are Bakhma, Shiranish, Aaliji, Kolosh, Sinjar, Gercus, Avanah, Pilaspi, lower Fars (Fat'ah), and Upper Fars (Injana) formations (Bamerni et al., 2021), as shown in Fig. 2.

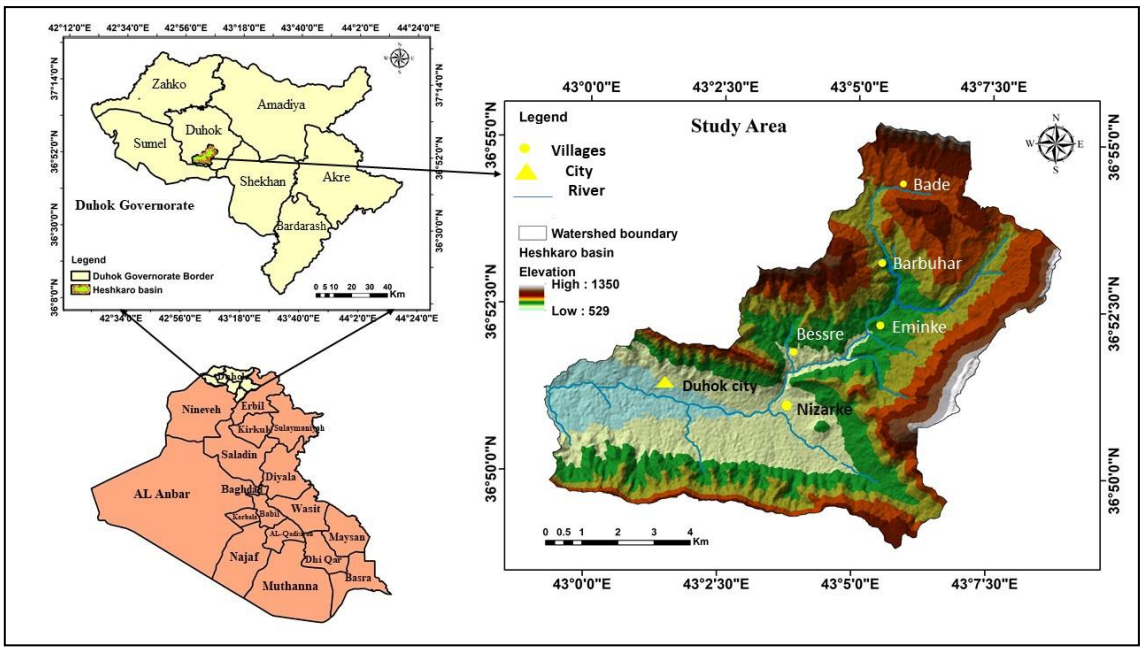

Fig. 1. Location map of the Heshkaro River basin

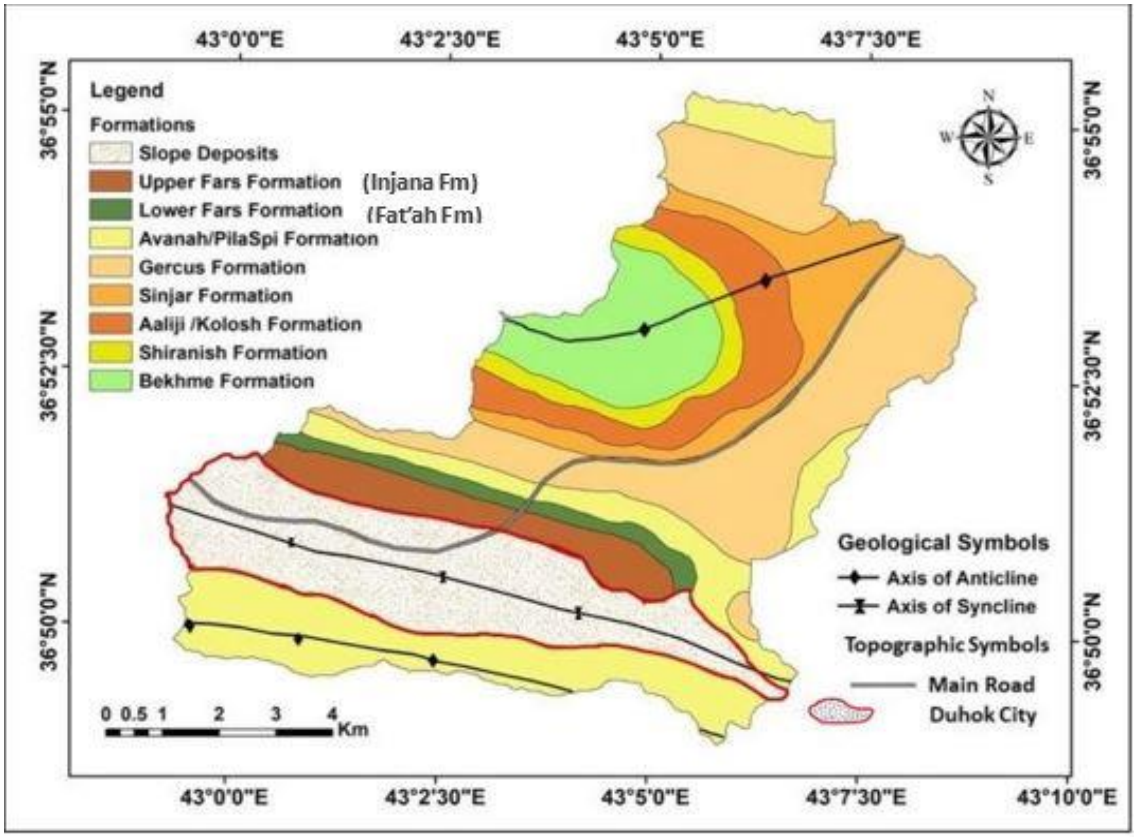

Fig. 2. Geological map of the Heshkaro river basin

2.2. Description of SWAT Model

The SWAT is a conceptual, semi-distributed, and computationally efficient hydrological model (Neitch et al., 2005). This model was developed by the United States Department of Agriculture (USDA) (Arnold et al., 1998; Oo et al., 2020), which is used to forecast the effect of land use/land cover change and land management practices on soil erosion, water quality, and sediment (Akoko et al., 2021; Wang et al., 2019). The model consists of two major divisions, the land phase and the routing phase, which are performed to simulate the hydrological response of watersheds. In the land phase, the hydrological mechanisms are estimated, including evapotranspiration, infiltration, surface runoff, subsurface water, etc. (Arnold et al., 1998; Abbas et al., 2017). The routing phase controls the movement of water amount and organic chemicals transported from the basin's river network to the outlet (Arnold et al., 1998; Shrestha et al., 2019). SWAT simulates the land phase of the hydrological cycle in the following Equation (1), based on a water balance formula (Arnold et al., 1998).

$$SW_t = SW_0 + \sum_{t=i}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{GW}), \quad (1)$$

Where SW_t= Final soil water content in mm, SW_0= Initial soil water content on day i (mm), t = the time (days), R_{day}= Amount of precipitation on day i (mm), Q_{surf}= Amount of surface runoff on day i (mm), E_a= Amount of evapotranspiration on a day i (mm), W_{seep}= Amount of water entering the vadose zone from soil profile on day i (mm), Q^{GW}= Amount of return flow on day i (mm).

The SWAT model is based on two very important methods for determining surface runoff. The first method (Green and Ampt, 1911) needs sub-daily precipitation data to estimate the infiltration rate based on hydraulic conductivity and the metric potential of the wetting front (Zhang et al., 2020). The second method is the Soil Conservation Service (SCS) curve number

The SCS runoff formula is an empirical equation (Equations 2 and 3) first used in the 1950s. The CN requires daily precipitation and depends on the soil's permeability, land use/land cover, and the soil's preceding water conditions (Musyoka et al., 2021). The SCS curve number equation can be written as follows (USDA-SCS, 1972).

$$Q_{surf} = \frac{(P-I_a)^2}{(p-I_a+s)}, \quad (2)$$

When $P > I_a$

$$s = \frac{1000}{cN} - 10, \quad (3)$$

Where: Q_{surf}: The surface runoff (mm), P: The precipitation depth (mm), Ia: The initial abstractions include the infiltration before the runoff, the interception, and the stored water in the soil (mm), S: The retention parameter (mm), CN: SCS Curve Number.

Generally, Ia = 0.2S, thus, Equation (2) is transformed into Equation (4)

$$Q_{surf} = \frac{(p-0{\cdot}2s)^2}{p-0{\cdot}2s}, \quad (4)$$

When $P > I_a$, the runoff will occur.

The SWAT Model depends on digital elevation models (DEMs), meteorological data, land use/land cover maps, and soil maps to run. Daily rainfall and the maximum and minimum temperatures are the most significant required parameters in meteorological data. The weather generator file could produce additional parameters. The file that generates the weather could also generate other parameters.

ArcSWAT is an extension of ArcGIS. In ArcSWAT, the basin is initially divided into sub-basins according to topographic characteristics and then further divided into several Hydrological Response Units (HRUs) based on specific slope, soil, and LU/LC combinations hydrological cycles.

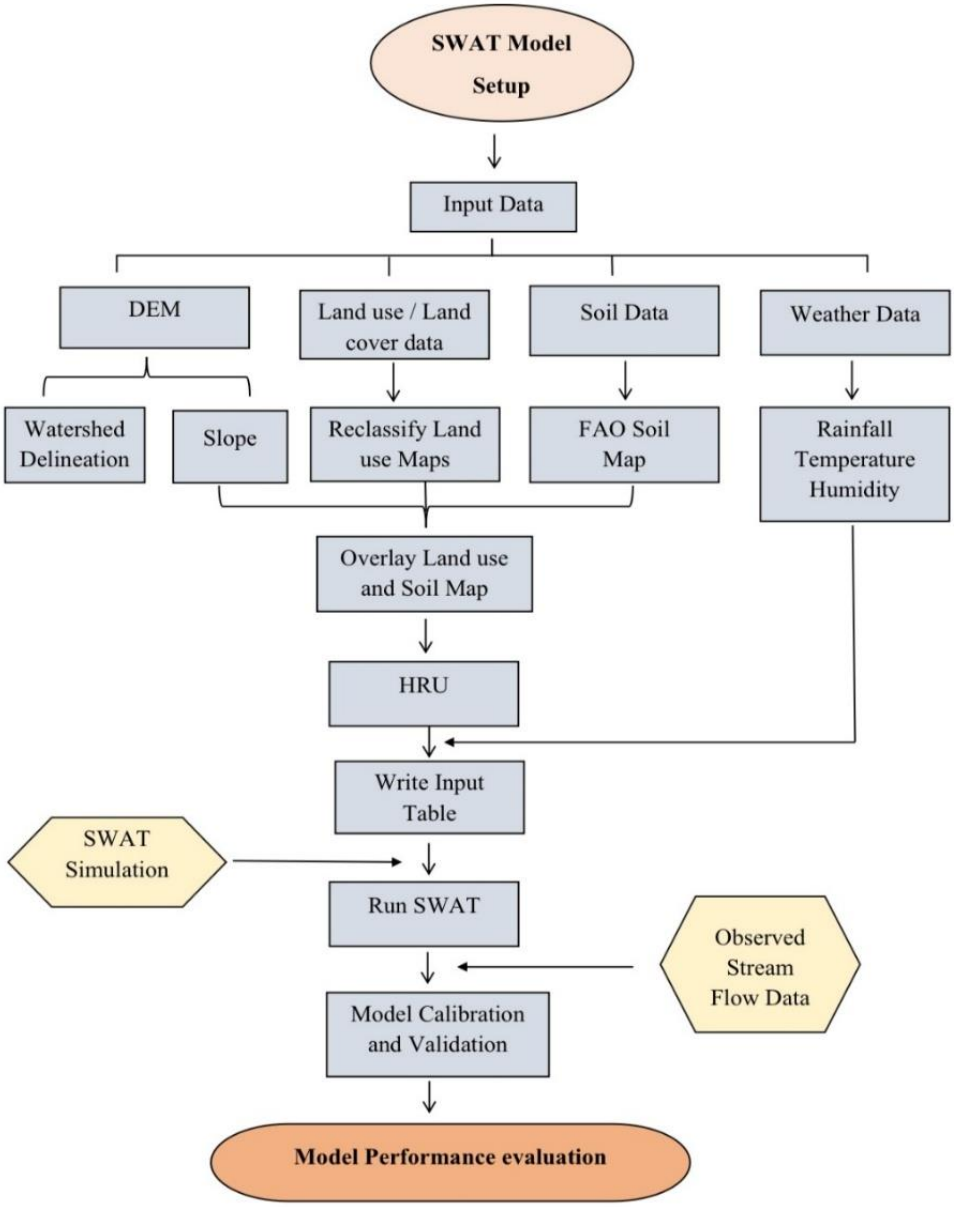

Fig. 3. Flowchart showing the steps of the SWAT setup model used in the Heshkaro River basin

2.3. SWAT Model Data Used and Analysis

2.3.1. Digital elevation model (DEM) data

The current study used the ALOS DEM (Advanced Land Observing Satellite Digital Elevation Model) with a spatial resolution of 12.5 m. This type of DEM is a Japanese satellite that was launched on January 24, 2006. The ALOS DEM is the radiometric terrain correction (RTC) process (RTC, 2022). DEM data was utilized to delineate the watershed and sub-basin, as well as identify the stream network and determine parameters of the basin such as slope, length, and gradient of the terrain. In this study, 25 sub-basins have been delineated, as shown in Fig. 4.

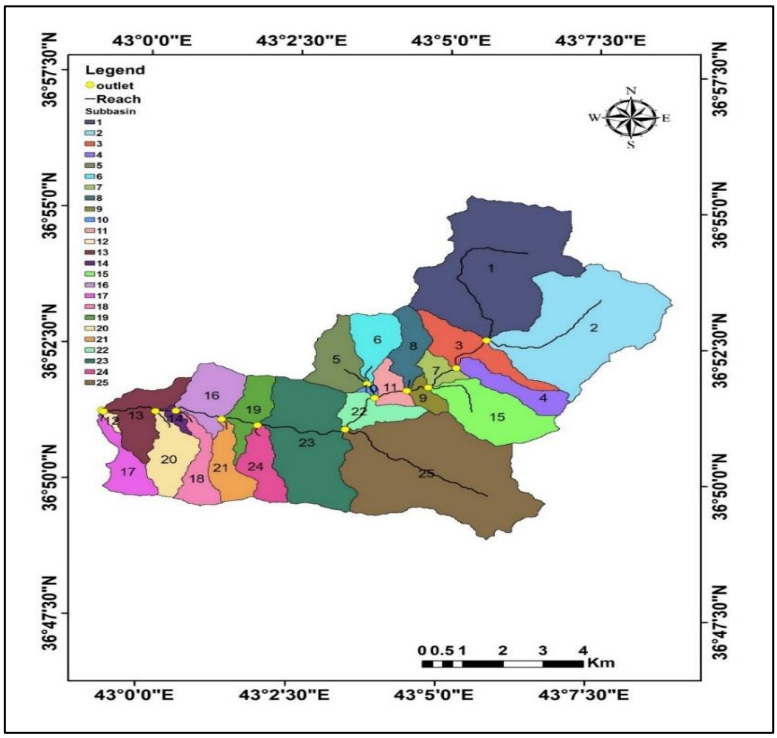

Fig. 4. Watershed delineation and subbasins of Heshkaro River using SWAT

2.3.2. Land use and land cover (LU/LC) distribution map

Satellite images of the years 1986,1990, 1996, 2000,2005, 2010,2016, and 2022 for several sensors were used in Table 1. The image source was the United States Geological Survey (USGS). The images were already corrected geometrically and radiometrically by NASA, then Atmospheric correction was used to remove the effects of the atmosphere on the reflectance values of satellite images. In this study, ATCOR software was used to improve the quality of the images used. This technique was produced by Dr. Richter of the German Aerospace Center—DLR (Khattab and Merkel, 2014). This software has been used after obtaining a license from the ReSe Applications GmbH company. The supervised classification method employed using the Maximum Likelihood Classifier on the 8 satellite images to acquire the main LU/LC classes (Urban area, Barren land, Vegetation area, and water).

Table 1. The attributes of satellite images used in the study

Satellite (Sensor)	Acquisition Data	Resolution (m)
Landsat 5 Thematic Mapper (TM)	20/02/1986	30
	03/03/1990	30
	16/02/1996	30
Landsat 7 The Enhanced Thematic Mapper Plus (ETM+)	03/02/2000	30
	16/02/2005	30
	02/03/2010	30
Landsat 8 The Operational Land Imager (OLI)	04/02/2015	30
Sentinel-2 MSI Multispectral Instrument (MSI)	13/02/2022	10

2.3.3. Soil data

Soil data for the study area was obtained from the FAO global soil dataset, which was collected using field surveys supported by remote sensing and environmental data and laboratory analysis, as well as with expert opinion. The soil dominant type in the study area has a loamy texture and belongs to the D hydrologic group, as shown in Fig.5. The soil belonging to this group is characterized by high runoff potential and low infiltration rates when thoroughly wetted.

2.3.4. Metrological data

Meteorological data is one of the main input sets for the hydrological process simulations model. Daily climatic data (precipitation, maximum and minimum temperatures, and relative humidity) were obtained from the Duhok metrological directorate and NASA. Meteorological data were used in the study area from January 1986 to August 2022.

2.3.5. Daily runoff data

Daily runoff data were obtained from the fieldwork. The runoff discharge was measured daily from January to May, several times following a rainfall storm event. The location of measurement was a regular cross-section working as a flume structure, as shown in Fig. 6.

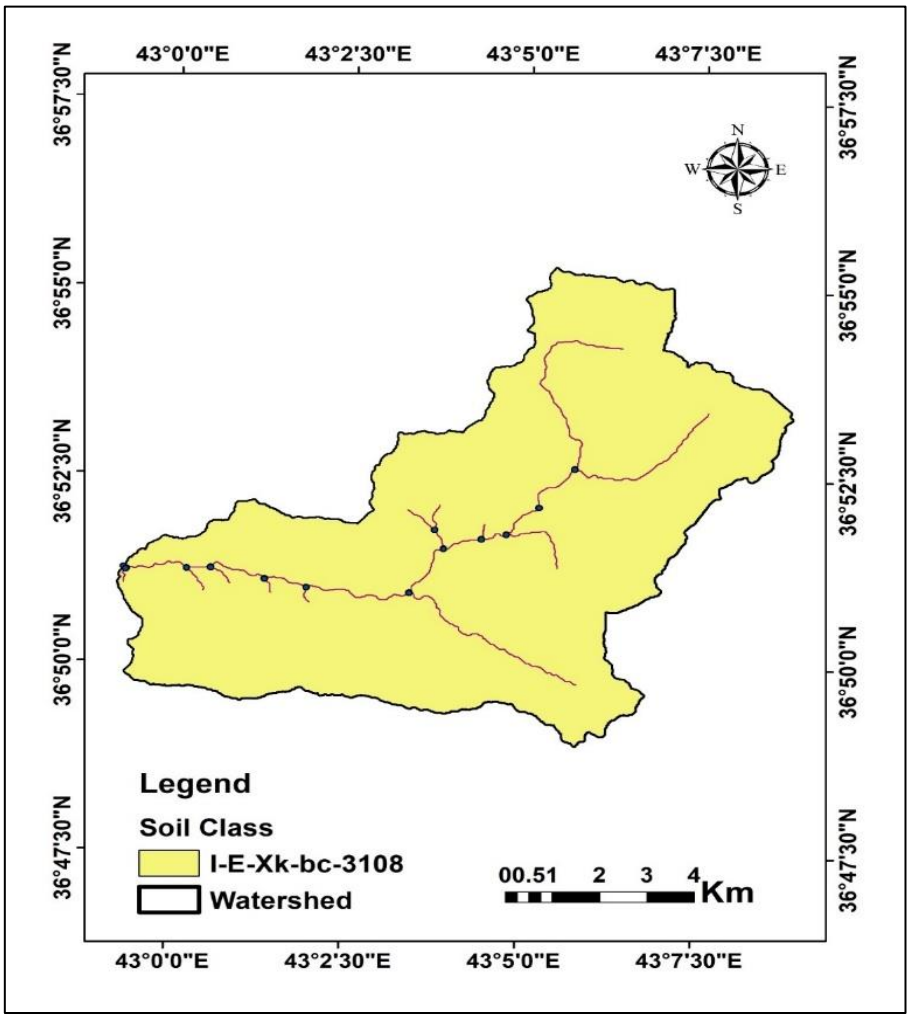

Fig. 5. Soil map of the study area using SWAT



Fig. 6. Runoff flow measurement in the fieldwork

2.4. SWAT Simulation

The model of study is ready for simulation after all the required data, such as rainfall, weather, and LULC, are imported into the SWAT workspace. The simulation for the rainfall-runoff model in this study was run to calculate the runoff of the Heshkaro River watershed.

2.4.1. SWAT model calibration and validation

Model calibration is an essential step for accurate results in hydrological modeling studies. Predicted values can be standardized through the calibration process by using the variance between two values (observed and simulated) in a given area to generate correction factors. For this study area, manual calibration of the SWAT model was applied for runoff discharge. The model was calibrated on the subbasin number 22 of the Heshkaro watershed. The process of calibration was carried out from 1/1/2022 to 31/3/2022. The runoff discharge from 1/4/2022 to 15/5/2022 was used for validation. The model was run using the best parameter output values after the manual calibration runs were completed.

2.4.2. Model performance

The Model performance evaluation is the important step to assess the Model and compare simulated and observed results. In the current study, four statistical measurements were used: the coefficient of determination (R^2), Nash Sutcliffe efficiency (NSE), and the root mean square error (RMSE) observation standard deviation ratio (RSR). Equations 5-7. More details on these measurements, including their significance and acceptable range of values, were explained by Moriasi et al. (2007).

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i^{obs}-O_i^{mean})*(P_i^{sim}-P_i^{mean})}{[\sum_{i=1}^{n}(O_i^{obs}-O_i^{mean})^2]^{0.5}*[\sum_{i=1}^{n}(P_i^{sim}-P_i^{mean})^2]^{0.5}}\right], \quad (5)$$

$$NSE = 1 - \frac{\sum\left(X_i^{obs} - X_i^{\mathrm{sim}}\right)^2}{\sum\left(X_i^{obs} - \mathrm{X}^{\mathrm{mean}}\right)^2}, \quad (6)$$

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sum\left(X_i^{obs} - X_i^{\mathrm{sim}}\right)^2}{\sum\ \left(X_i^{obs} - \mathrm{X}^{\mathrm{mean}}\right)^2}, \quad (7)$$

Where X_i^{obs} = observed value, X_i^{sim}= simulated value, and X^{mean} = the mean of the observed value.

3. Results and Discussion

3.1. LULC Change

The spatial distribution of LULC classes in percentage and km^2 for the years 1986, 1990, 1996, 2000, 2005, 2010, 2015, and 2022 are shown in Fig. 7, Table 2. The changes in the land use and land cover classes of the study area from 1986 to 2022 are shown in Fig. 8. The figure demonstrates that the urban area gradually grew from 3.65 km^2 in 1986 to 13.91 km^2 in 2022. This growth resulted in a decrease in the areas covered by vegetation and water and an increase in barren land. The areas covered by vegetation decreased from 28.42 km^2 (35.05%) in 1986 to 15.81 km^2 (19.50%) in 2022, although the vegetation area increased by 12.28 km^2 (15.15%) in 2000 to 15.81 km^2 (19.50%) in 2022 and the areas covered by water decreased from 0.82 km (1.01%) in 1986 to 0.40 km^2 (0.49%) in 2022. Furthermore, the barren lands covered the largest area between 1986 and 2000 but declined by 33.39 km^2 (41.18%) in 2005 due to snow covering. After that, it was discovered that the amount of barren land decreased gradually between 2010 and 2022.

Table 2. Magnitude of land use/land cover type for 1986, 1990, 1996, 2000, 2005, 2010, 2015, and 2022 in the Heshkaro River basin

Years	**1986**		**1990**		**1996**	
Classes	**Km^2**	**%**	**Km^2**	**%**	**Km^2**	**%**
Urban area	3.65	4.5	4.96	6.12	5.25	6.48
Barren land	48.2	59.45	49.10	60.56	50.08	61.77
Vegetation area	28.42	35.05	26.50	32.68	25.18	31.05
Water	0.82	1.01	0.52	0.64	0.57	0.7
Years	**2000**		**2005**		**2010**	
Classes	**Km^2**	**%**	**Km^2**	**%**	**Km^2**	**%**
Urban	6.25	7.71	7.25	8.94	8.8	10.85
Barren land	64.84	79.96	33.39	41.18	59.5	73.39
Vegetation	9.60	11.84	8.56	10.55	12.28	15.15
Water	0.40	0.49	0.38	0.47	0.50	0.61
Snow	-	-	31.51	38.86	-	-
Years	**2015**		**2022**		**Change 1986 - 2022**	
Classes	**Km^2**	**%**	**Km^2**	**%**	**Km^2**	**%**
Urban	11.28	13.91	13.86	17.09	10.21	12.59
Barren land	54.46	67.17	51.02	62.92	2.82	3.47
Vegetation	15.04	18.55	15.81	19.50	-12.61	-15.55
Water	0.30	0.38	0.40	0.49	-0.42	-0.52

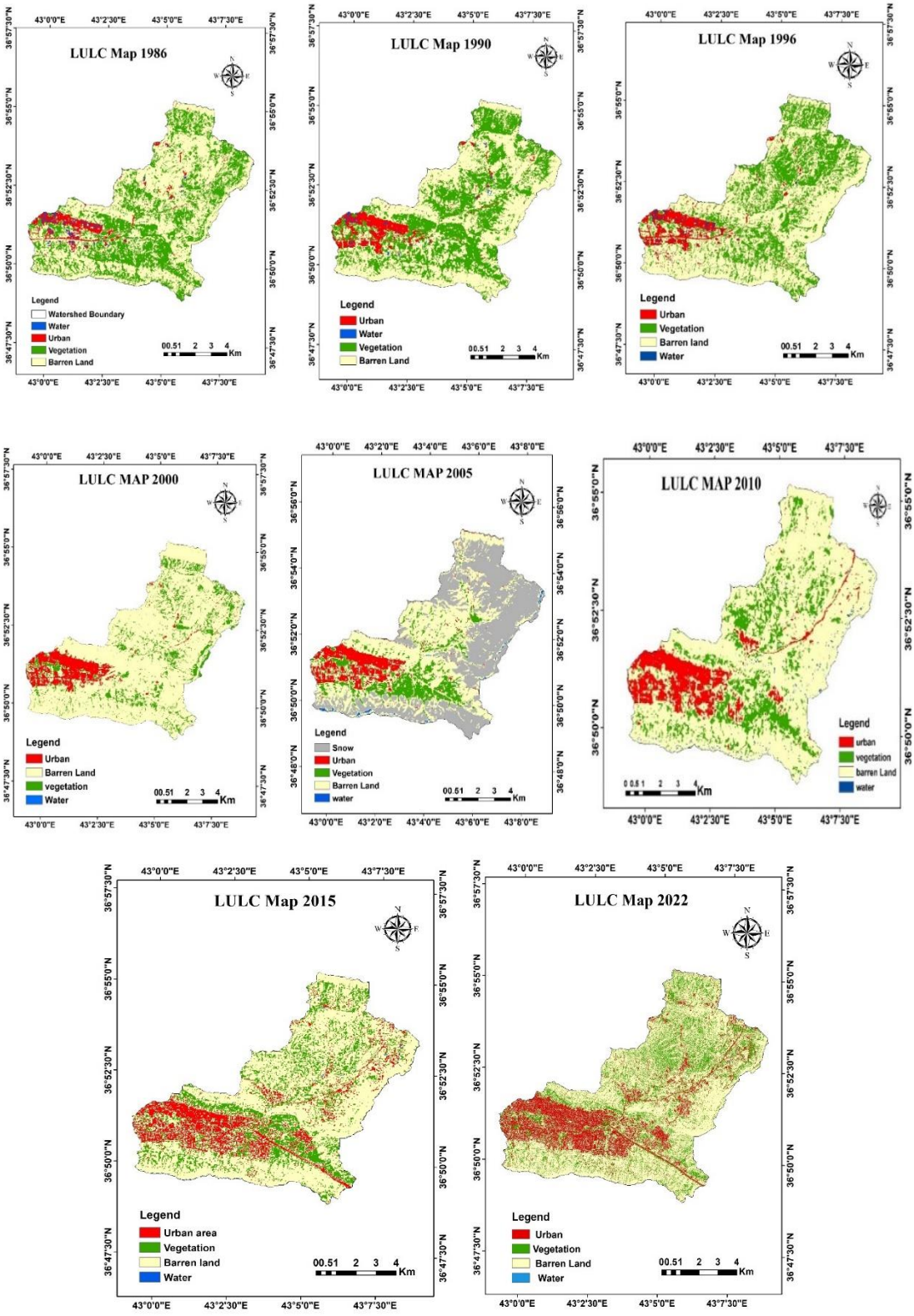

Fig .7. Land use land cover map of 1986, 1990, 1996, 2000, 2005, 2010, 2015, and 2022

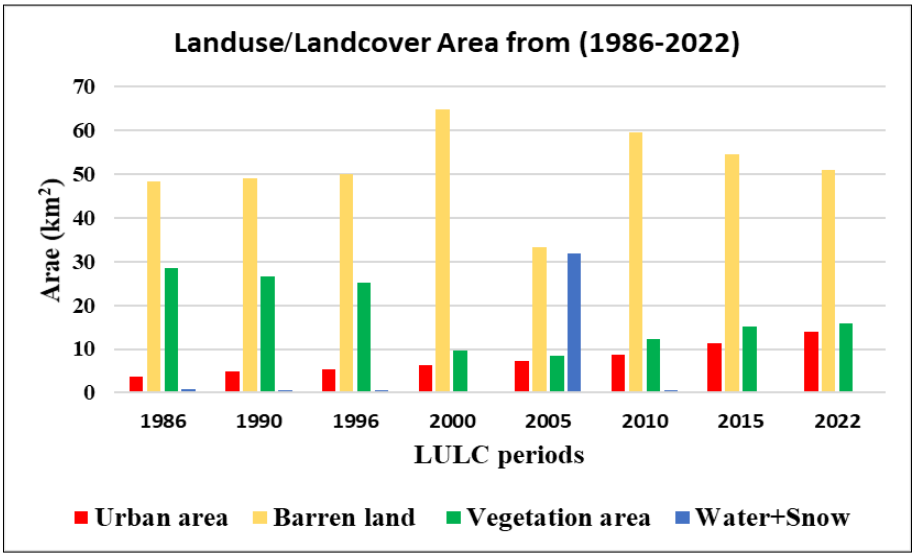

Fig. 8. Change detection of LULC classes from 1986 to 2022

3.2. SWAT Model Calibration and Validation

The SWAT model for the runoff was calibrated to maximize the model efficiencies. The model was manually calibrated for ten parameters (CN2, ALPHA-BF, GW_DELAY, GW_REVAP, RECHARGE_DP, ESCO, EPCO, SOL-AWC SOL—K, SLSUBBSN). Table 3 shows the values of the parameters used in the calibration. This process changes the values of the parameters in an iterative trial-and-error procedure.

Table 3. Ranges and best-fitted values of the model calibration

Rank	Parameters	Description	Range	Calibrated value
1	CN2	SCS runoff curve number	40-95	75
2	ALPHA-BF	Baseflow alpha factor	0-1	0.1
3	GW_DELAY	Groundwater delay time	0-100	85
4	GW_REVAP	Groundwater “revap" coefficient	0-1	0.02
5	RECHARGE_DP	Recharge to deep aquifer	0-1	0.5
6	ESCO	Soil evaporation compensation factor	0-1	0.5
7	EPCO	Plant water uptake compensation factor	0-1	0.1
8	SOL-AWC	Available water capacity	0-50	10
9	SOL-K	Saturated hydraulic conductivity	-50 -+50	0.01
10	SLSUBBSN	Average slope length	-50 -+50	0.02

During the calibration process, the curve number (CN) value gradually decreased, and the value of the recharge deep increased. Thus making the peak simulated discharge match with the observed discharge. Fig. 9 shows the results of the calibration for the daily flow, which demonstrates a very good match between the observed and simulated daily flows. Furthermore, for the flow calibration period, the estimated R^2, NSE, and RSR are 0.92, 0.91, and 0.04, respectively, which indicates a good model performance evaluation according to SWAT assessment criteria (Table 4; Fig. 10A).

The calibrated model efficiency was validated. Rainy events for two months (April and May) of 2022 were used for that. Fig.9 shows the validation result for the daily flow model of the study area. The validation simulation showed a good match between the observed and simulated daily flow data, R^2 value of 0.85, NSE of 0.90, and RSR of 0.01 (Fig. 10B). The model performance values for flow simulation calibration and validation are appropriate. This shows that the model successfully captured the physical processes in creating flows in the watershed. As a result, the model simulations can be applied to various management of water resources and development issues.

After verifying the model efficiency, it was used to estimate the daily surface runoff of the Heshkaro watershed during the specific periods (1986, 1990, 1996, 2000, 2005, 2010, 2015, and 2022), as shown in Fig. 11.

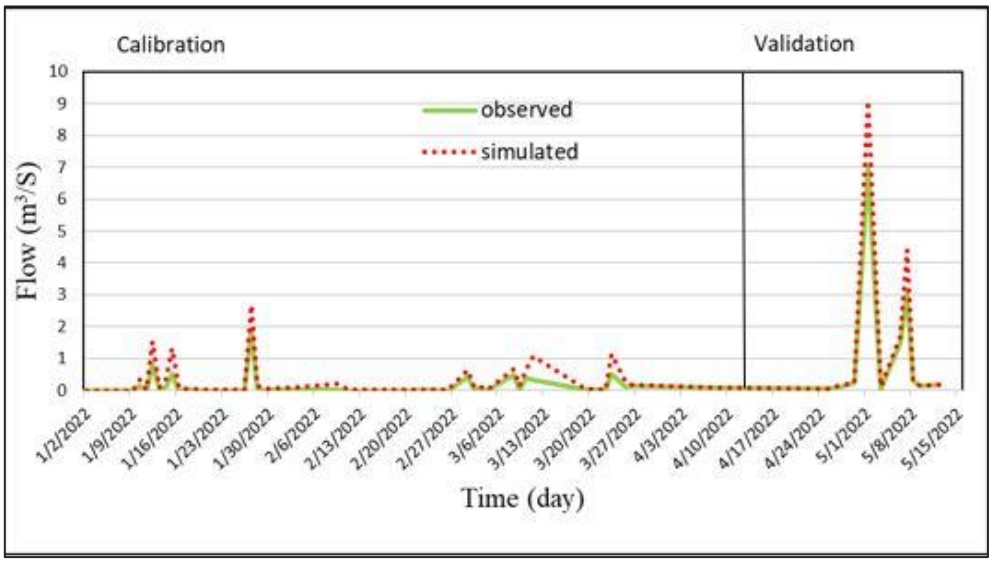

Fig. 9. Calibration and validation of the SWAT model for daily observed and simulated runoff (from January 1 to May 15, 2022)

Table 4. SWAT performance evaluation criteria (Moriasi et al., 2007; Moriasi et al., 2015)

Performance Evolution	R^2	NSE	RSR
Very good	0.80 to 1	0.75 to1	0.00 to 0.50
Good	0.70 to 0.80	0.65 to 0.75	0.50 to 0.65
Satisfactory	0.60 to0.70	0.50 to 0.65	0.60 to 0.70
Unsatisfactory	$R^2 \leq 0.60$	NSE ≤ 0.50	RSR ≥ 0.70

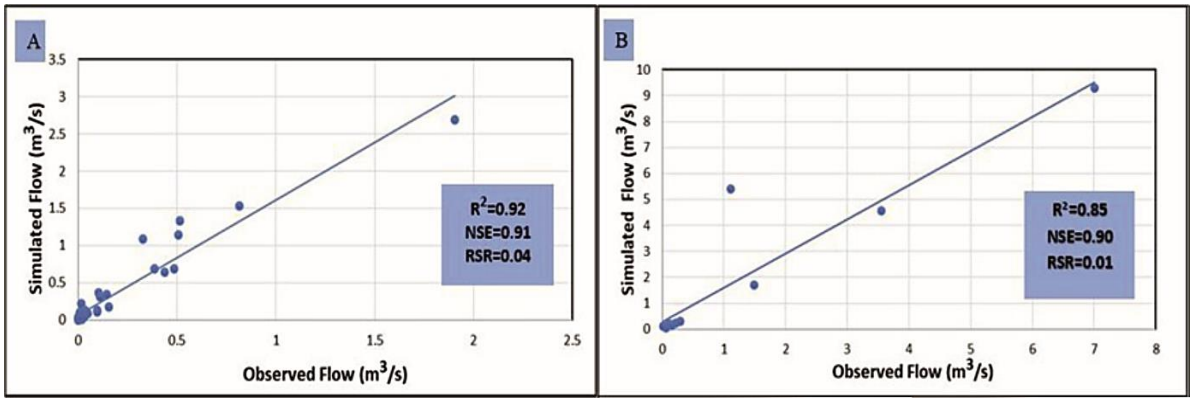

Fig .10. Scatter plot between observed and simulated SWAT model: (A) calibration (B) validation

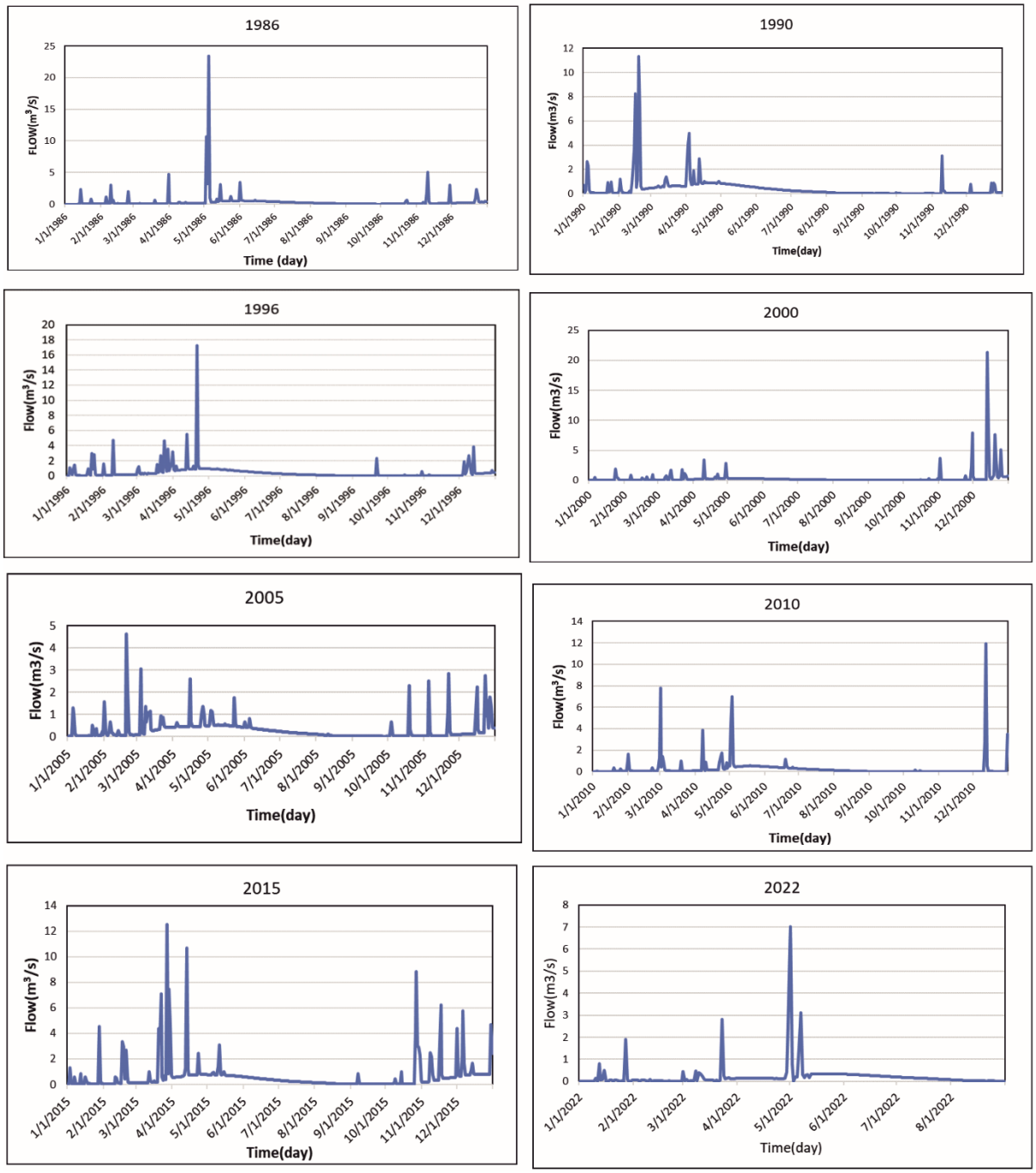

Fig. 11. Daily surface runoff during the years 1986, 1990,1996, 2000, 2005, 2010, 2015, and 2022

3.3. Impact of LU/LC Changes on the Hydrological System

The impact of land use and land cover on the surface runoff of the Heshkaro River was assessed. Eight separate simulation runs were carried out on eight LU /LC maps for the period of 1986-2022 with a constant rainfall amount. The results indicated that each of the classes of the urban area, barren land, and vegetation cover has a different impact on the runoff. In general, the vegetation cover has a more direct reverse effect on the runoff, where it can produce less surface flow but more groundwater flow and evapotranspiration (Tan et al., 2022). The changes in the barren land show a positive response to the runoff which produces more surface flow but less groundwater flow and evapotranspiration, and the same with urban areas. Fig .12 shows the flow increasing with expanding urban areas and barren land

and decreasing with increasing vegetation cover from 1986 to 2022. The growth of urbanization at the expense of green lands may have a significant impact on the environment of cities and lead to several environmental issues, such as disastrous urban flooding.

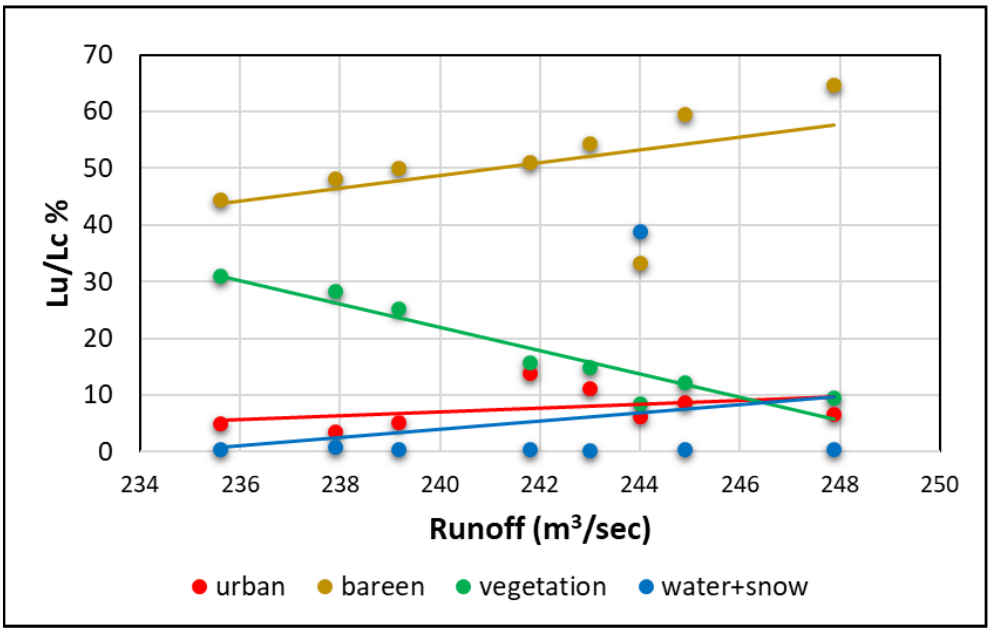

Fig. 12. The expected impact of the LU/LC on runoff for the study area of years 1986, 1990,1996, 2000, 2005, 2010, 2015, and 2022

4. Conclusions

The watershed analysis and forecasting amount of the surface runoff is an utmost priority for catchment area management. This work proves the effectiveness of the integration between GIS and remote sensing techniques in detecting and analyzing spatiotemporal land use /land cover dynamics. Moreover, it provides a fundamental view of the hydrological behavior of a watershed through the flooding time. The land use and land cover of the Heshkaro River watershed from 1986 to 2022 experienced a significant change. It is concluded that urban and barren land will be increased and the vegetation area and water regions will be decreased over time as a consequence of human activities of the infrastructure. The impact of land use and land cover on the surface runoff of the Heshkaro River concluded that flow increases with expanding urban areas and barren land and decreases with increasing vegetation cover from 1986 to 2022. The study concludes that there is a need to provide the requirement for deep management of the Heshkaro River watershed to secure the environmental sustainability of the basin. The study recommended establishing gauging stations and conducting detailed soil surveys to enhance the accuracy of results.

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