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Scenario-based modelling of ecological security: Integrating land use and climate change impacts in the Lavasanat Watershed

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Abstract

Understanding the impact of land-use and climate change on ecosystem services is crucial for ecological security assessments. This study examines spatiotemporal land-use/land-cover (LULC) changes in the Lavasanat Watershed, Tehran, Iran (2000–2040) and evaluates their effects on water yield under different management and climate scenarios. Four LULC scenarios were defined: S1 (business-as-usual), S2 (pessimistic), S3 (realistic), and S4 (optimistic). Additionally, three climate scenarios (B1, N, and M) were incorporated into the analysis. The InVEST model was used to simulate water yield variations, while CA-Markov and LARS-WG5 projected future LULC and climate conditions. Findings indicate a 1.92-fold increase in water yield in residential areas from 2000 to 2020. The highest water yield was recorded under S2N (37.64 million m³ watershed-wide, 35.09 million m³ in residential areas), while the lowest was observed under S4M (8.33 million m³ watershed-wide, 7.35 million m³ in residential areas). All scenarios suggest that urban expansion will continue to drive water yield increases while reducing ecologically valuable lands by 2040. These findings highlight the critical role of sustainable land-use planning in mitigating environmental degradation and ensuring ecological security in rapidly urbanizing watersheds.

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Introduction

Numerous human activities have detrimental effects on ecosystems, leading to the destruction of their structures and disruption of ecological processes (Salvati & Carlucci, 2014). Urbanization is one such human activity that, while driving economic development, gives rise to substantial environmental challenges, including rapid changes in land use/cover (He et al. 2014; Li et al., 2011; Peng et al., 2017; Kong et al., 2017; Qiao et al., 2024). These rapid land use/land cover (LULC) changes tend to have fairly severe long-term ecological and environmental consequences, potentially causing a rapid decline in the quality of environmental ecosystems in a very short period of time (Wu et al., 2019). A variety of concepts, such as ecological carrying capacity and ecological security, have been specifically introduced to address this problem (Li et al., 2014). In many cities that have expanded haphazardly due to the subjective nature of initial planning and its lack of scientific rigor, significant environmental spaces essential for maintaining ecological security have been converted into residential areas (Van Vliet et al., 2019). Nevertheless, today, ecological security is rightfully acknowledged as a significant strategic concern from social, economic, and political perspectives (Li et al., 2019; Hua and Bruijnzeel, 2022). Indeed, even the preservation of ecological security in a small area can significantly contribute to the preservation of global and regional ecological security, consequently supporting sustainable economic growth and development (Fu et al., 2015). The concept of a landscape ecological security pattern was initially introduced by Yu in 1996, who asserted that ecological security represents an effective approach for safeguarding crucial ecological processes and landscape patterns (Yu, 1995, 1996). In this context, Ecological Security Patterns (ESPs) encompass the solutions aimed at preserving the integrity of ecosystem structures, functions, and processes (Zhang et al., 2015).

The capacity to identify and safeguard the most critical aspects of landscapes and ecological processes renders ESPs a potent tool for upholding ecological security (Yu, 1996; Kattel et al., 2013; Peng et al., 2018a). Ecological security studies can be conducted at various levels, including city (Peng et al., 2019; Zhang and Li, 2024), provincial (Peng et al. 2018b), regional (Zhang et al., 2017), and even national and international scales (MacMillan et al., 2007).

Landscape ecological security pertains to the environmental health and sustainability of a landscape's resources and ecosystems, as well as their capacity to deliver ecological services and fulfill the ecological needs of future generations in a sustainable manner (Khramtsov 2006; Feng et al., 2017). In essence, this concept assesses whether a landscape's ecosystems possess internally sustainable structures and provide healthy functional services (Novin et al., 2022). As ecological security assessments form the cornerstone of urban ecology research (Arrow et al., 1995; Zhou, 2007), the utilization of ESPs is essential for comprehending how to analyze and address ecological security concerns arising from rapid urbanization (Peng et al., 2019). An integral aspect of ecological security assessments involves the set of indicators that can be employed to evaluate how an ecosystem has evolved in temporal and spatial dimensions (Zhao et al., 2006). Among these indicators, one category is ecosystem services (Chen et al., 2018). In recent years, there has been a burgeoning interest in utilizing ecosystem services within ecological security assessments (Wang & Pan, 2019; Qin et al., 2019) to establish a decision-making platform for achieving a harmonious balance between socioeconomic development and ecosystem preservation (Chen et al., 2018).

Concerns about ecological security began to rise in the late 1970s with increasing awareness about the wide variety of phenomena that threaten the integrity of ecosystems (Peng et al., 2019; Li et al., 2019; Wang et al., 2019; Liu et al., 2018). Since then, ecological security has been the subject of a great number of studies conducted all around the world (Liu et al. 2022; Cao et al., 2022; Yang & Cai, 2020; Xie et al., 2020; Wang & Bao, 2021; Liu et al., 2021; Ghosh et al., 2021). There are various methods for analyzing and assessing ecological security, including the Pressure-State-Response method (Tang et al., 2020; Ma et al., 2019; Zhao et al., 2022; Zhang et al., 2025), the Driver-Pressure-State-Impact-Response (DPSIR) framework (Wang et al., 2016; Chen and Wang, 2020; Peng et al., 2021; Chen et al., 2022), the system clustering method (Lundquist & Sommerfeld, 2002), ecological footprint and ecological risk methods (Li & He, 2011; Yang and Cai, 2020; Li et al., 2014; Zhang et al., 2018; Li et al., 2019; Zhao et al., 2018; Liu et al., 2021; Oertel, 2024), the comprehensive index method (Bartel, 2000), the fuzzy comprehensive evaluation method (Han et al., 2015), the GIS method (Xie et al., 2020; Feng et al., 2017), multi-criteria decision-making methods (Gao et al., 2018; Ghosh et al., 2021), the ecosystem services model (Huang et al., 2017; Su et al., 2022; Yang et al., 2022), the landscape model (Yu et al., 2018; Ma et al., 2019), and the CA-Markov model (Ghosh et al., 2021; Xie et al., 2020).

In this study, ecological security assessments were conducted using a combination of GIS-based methods, the ecosystem services model, and the CA-Markov model. As the study aimed to assess ecological security levels for the years 2000, 2010, and 2020, and predict conditions for 2040 under various LULC and climate scenarios, the InVEST 3.7.0 ecosystem services model was employed to quantify water yield.

Water yield refers to the portion of precipitation that remains available as surface runoff and groundwater recharge after evapotranspiration losses. It is directly influenced by land-use changes and climate variability, making it a key indicator for assessing ecosystem services and water resource availability.

The CA-Markov model (IDRISI) and the Scenario Generator tool (InVEST 3.7.0) were used to generate LULC projections for 2040, while LARS-WG5 simulated climate scenarios for the same period. LULC classification was conducted using ENVI-based methods, and GIS-based techniques were applied for map generation.

These analyses yield scientific data gathered and compiled with a comprehensive approach, aiming to assess ecosystem services, which, within the scope of this paper, are anticipated to enhance the management of the Lavasanat Watershed near the city of Tehran. Over the past few decades, rapid urban development in and around the Tehran metropolitan area has triggered substantial LULC changes in this region. One significant challenge facing this watershed is the expansion of residential areas, particularly within the Lavasanat area, resulting in a significant reduction in the coverage of ecologically valuable land. This underscores the urgency of addressing the concerns in this watershed.

This study aims to achieve the following objectives: 1. Temporal-spatial analysis of LULC changes from 2000 to 2040, 2. Analysis of ecosystem services (water yield) within various LULC and climate change scenarios, and 3. Analysis of changes in ecological security from 2000 to 2040 within different LULC and climate change scenarios, based on ecosystem services (water yield).

Materials And Methods

The methodology of this study consisted of several steps: firstly, an analysis of the temporal-spatial changes in LULC within the Lavasanat Watershed; secondly, the simulation of LULC and climate changes using CA-Markov, Scenario Generator, and LARS-WG5 to determine the temporal-spatial changes in ecological security in the area; and finally, an examination of ecological security changes under four LULC scenarios and three climate change scenarios (Figure 1).

Study area

The Lavasanat Watershed, covering an area of 52,933 hectares, is situated in Shemiranat County in the north-northeast of Tehran Province (Figure 2). It encompasses a town named Lavasan and two villages named Lavasan-e-Bozorg and Lavasan-e-Kuchak, and it is bordered by Noor County to the north, Karaj County to the west, Damavand County to the east, and the city of Tehran to the south. Lavasanat Watershed is located within geographical coordinates 35°46′-36°03′N and 51°24′-51°50′E (Rahmani Fazli, 2016) and comprises the Kand, Afje, and Lavarak sub-watersheds. The primary rivers in these sub-watersheds and their tributaries flow directly into the Latyan Dam reservoir (Talari, 2016).

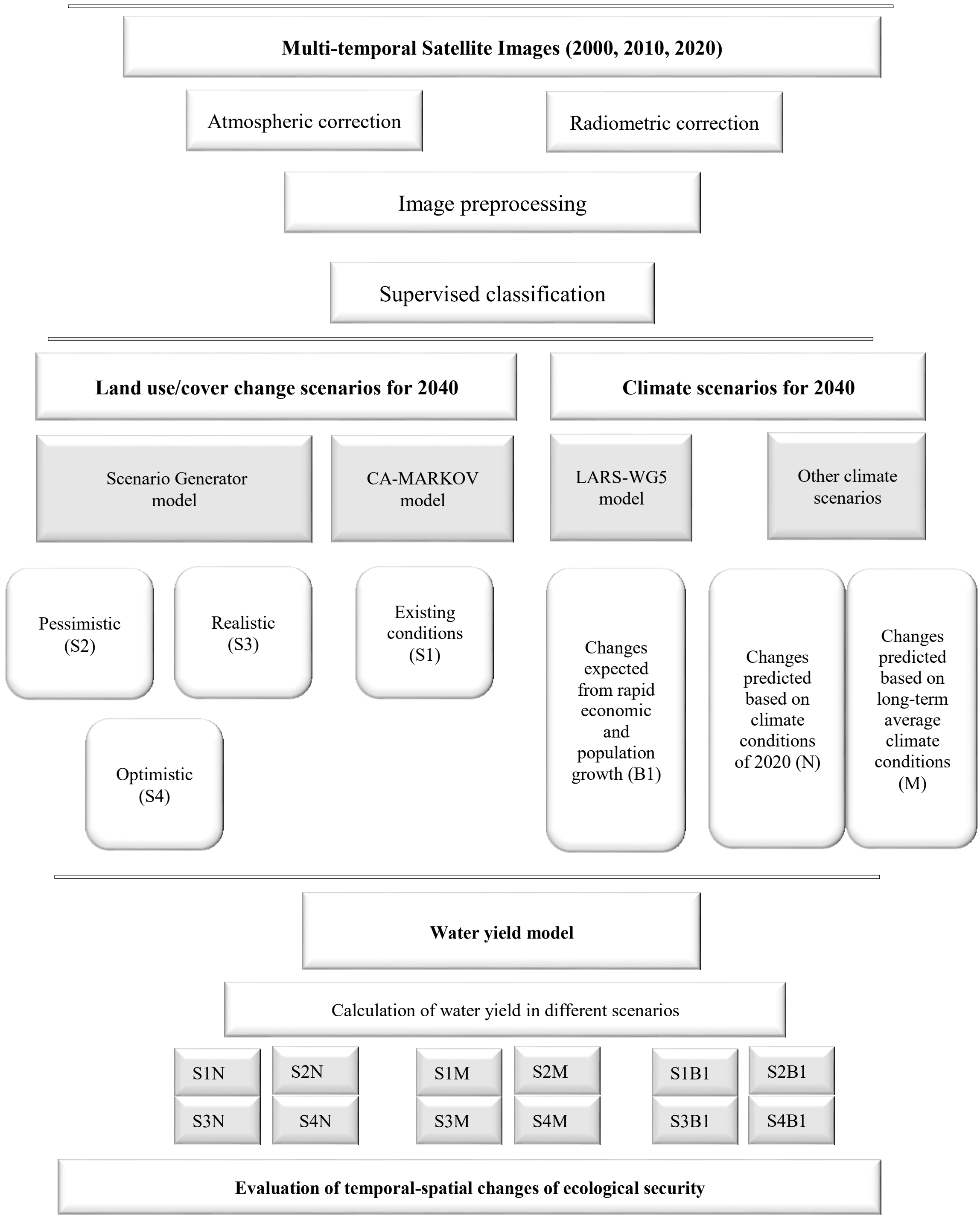

Figure 1. Flowchart of the study

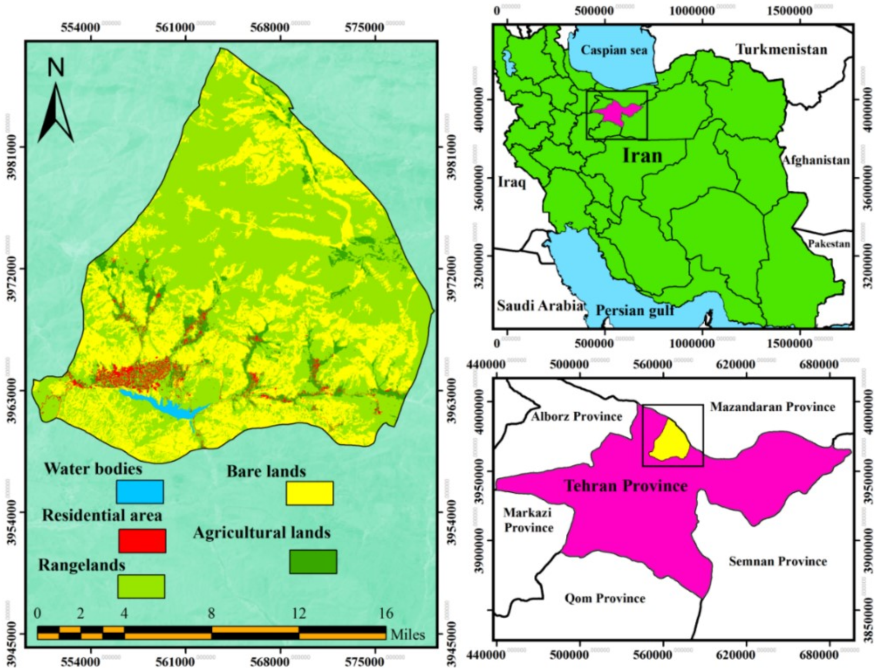

Figure 2. Geographical location of Lavasanat Watershed and the LULC map of the area for the year 2020

Methodology

We applied an integrated methodological framework to analyze LULC changes and assess their impacts on ecological security within the Lavasanat Watershed. The methodological process involved LULC classification, future land-use projections, climate scenario generation, and water yield modeling using InVEST 3.7.0.

LULC Mapping and Classification:

LULC maps for 2000, 2010, and 2020 were generated using Landsat satellite images (Table 1) and high-resolution Google Earth imagery to improve classification accuracy in areas with dispersed residential development. Image processing was conducted in ENVI 5.3 and ArcGIS 10.5 using the supervised maximum likelihood classification method, categorizing the study area into five classes: (1) residential areas, (2) bare lands, (3) rangelands, (4) water bodies, and (5) agricultural lands. Classification accuracy was validated using overall accuracy (OA) and the kappa coefficient (KC).

Table 1. Specification of satellite images used in the study

Characteristics	Resolution/sensor	Path/row	Resolution panchromatic	Data of acquisition
Satellite				
Landsat 7[a]	ETM+	164/35	30	May 15, 2000
Landsat 7[a]	ETM+	164/35	30	May 25, 2010
Landsat 8[a]	OLI	164/35	30	May 12, 2020

[a] These data were collected from the official website of US Geological Survey (USGS) (http://glovis.usgs.gov)

LULC Change Projection Using CA-Markov Model

Future land-use scenarios for 2040 were simulated using the CA-Markov model in IDRISI. The Markov chain component was used to determine transition probabilities based on historical LULC changes from 2000 to 2020, while cellular automata (CA) spatially allocated projected changes. Model training was performed using LULC data for 2000 and 2010 to generate transition probabilities, which were then applied alongside the 2020 LULC map to predict

2040 changes under the business-as-usual scenario (S1).

To account for varying urban development strategies, three additional scenarios were developed using the Scenario Generator tool in InVEST 3.7.0:

S2 (Pessimistic): Uncontrolled urban expansion leading to a severe decline in ecological security.

S3 (Realistic): Managed urban expansion maintaining existing ecological security levels.

S4 (Optimistic): Urban development incorporating conservation strategies to enhance ecological security.

Climate Scenario Generation Using LARS-WG5

To assess climate variability impacts, LARS-WG5, a stochastic weather generator, was used to simulate climate conditions for 2040. This model statistically downscales broader climate projections to generate site-specific climate variables. Three climate scenarios were developed:

B1 (High-Impact Scenario): Assumes rapid economic and population growth, leading to higher climate variability, altered precipitation patterns, and increased evapotranspiration.

N (Baseline Scenario): Assumes climate conditions remain unchanged from 2020, serving as a reference for future deviations.

M (Long-Term Stability Scenario): Reflects historical climate trends, assuming consistent precipitation and evapotranspiration patterns.

The primary distinction among these scenarios lies in the degree of climate variability, with B1 representing the most extreme changes, while M assumes relative climatic stability.

Water Yield Modeling Using InVEST 3.7.0

To quantify the impact of LULC and climate changes on water yield, this study employed the Water Yield Model in InVEST 3.7.0. This model estimates water yield by balancing precipitation inputs with evapotranspiration and infiltration losses, considering land-use characteristics. Input data included:

Precipitation and evapotranspiration maps.

Root-restricting layer depth.

Land-use/vegetation characteristics.

Simulations were performed for 2000, 2010, and 2020, with projections extended to 2040 under the four LULC scenarios (S1-S4) and three climate scenarios (B1, N, M). The results enabled an evaluation of hydrological responses to urban expansion and climate change.

Model Assumptions and Limitations

CA-Markov Model:

This model assumes that historical LULC change trends will continue, which may not fully account for unforeseen policy interventions or socio-economic shifts.

Transition probabilities were derived from observed changes between 2000 and 2020, ensuring realistic projections.

LARS-WG5 Model:

Generates localized climate scenarios but does not incorporate global climate dynamics.

Long-term climate variability may be underrepresented due to reliance on historical data trends.

InVEST Water Yield Model:

Does not explicitly model surface runoff processes but provides an estimate of total water availability, encompassing both surface runoff and groundwater recharge.

Results are sensitive to input data quality, particularly precipitation and evapotranspiration datasets.

By integrating CA-Markov, LARS-WG5, and InVEST, this study provides a robust framework for evaluating ecological security trends and informing sustainable land-use planning in the Lavasanat watershed.

Results

Analysis of LULC changes from 2000 to 2020

An analysis of LULC changes from 2000 to 2020 revealed significant trends. Figure 3 illustrates the alterations in the area's LULC zones during the periods of 2000 to 2010 and 2020. The findings indicate a consistent and substantial expansion of residential areas over the two-decade timeframe spanning from 2000 to 2020. This expansion can be primarily attributed to population growth, increasing housing demands, and the subsequent process of urbanization.

These maps also provide insights into the changes in the area's agricultural lands within the watershed over the course of 20 years. Notably, there has been a consistent decrease in the extent of agricultural lands during this period. Moreover, the area of rangelands in the watershed experienced a reduction in the first decade (2000-2010), followed by a recovery in the subsequent decade (2010-2020). In fact, the rangeland area exceeded the 2000 levels by the end of the two-decade period, likely due to increased precipitation.

Simultaneously, bare lands within the region exhibited a continuous reduction in their extent over the same two-decade timeframe. This decrease can be attributed to their proximity to residential areas, which often undergo expansion and development. For more detailed information, please refer to Table 2.

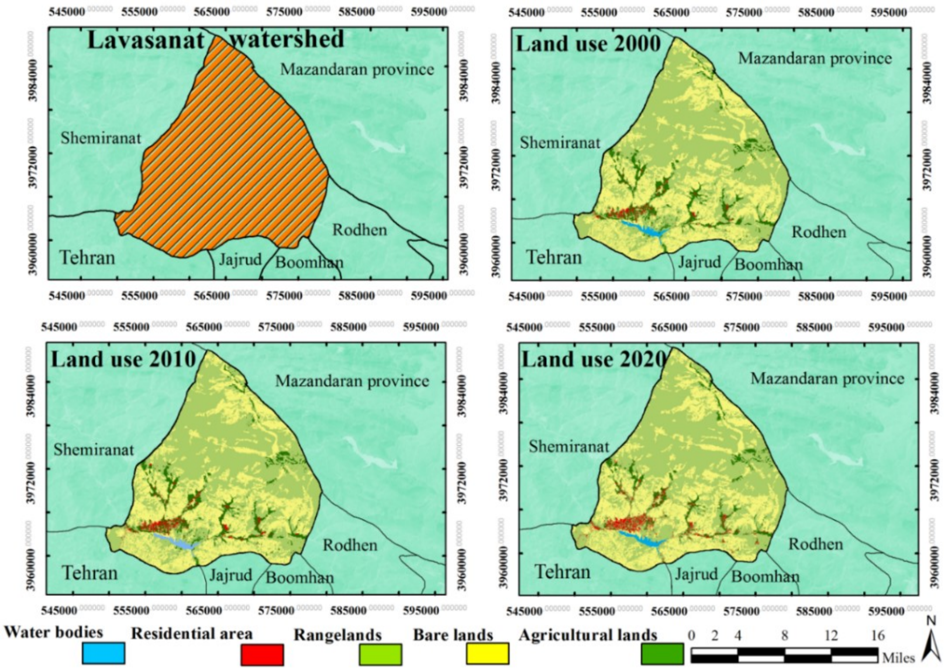

Figure 3. Land use/cover changes in Lavasanat Watershed between 2000 and 2020

Table 2. Area of LULC classes in Lavasanat Watershed in 2000, 2010, and 2020

LULC	2000		2010		2020	
	Ha	%	Ha	%	Ha	%
Water bodies	356.497428	0.67	358.83	0.68	358.744057	0.67
Agricultural lands	3324.36776	6.28	3204.586317	6.05	2228.660076	4.21
Bare lands	19117.362915	36.11	19079.384967	36.04	19015.562751	35.92
Rangelands	29704.299642	56.11	29601.808827	55.92	30289.395861	57.22
Residential area	430.629936	0.82	688.551379	1.31	1040.794871	1.97
Overall accuracy	95.72		96.26		95.32	
Kappa coefficient	0.948		0.943		0.936	

Prediction of the expansion of residential areas in Lavasanat Watershed in the four scenarios using CA-Markov and Scenario Generator

Figure 4 illustrates the anticipated LULC changes by 2040 under four defined scenarios:

S1 (Existing Conditions): Continuation of current urban growth trends with moderate expansion and gradual ecological decline, without major policy interventions.

S2 (Pessimistic): Uncontrolled urban sprawl due to a lack of land-use regulations, leading to significant environmental degradation and loss of ecologically valuable land.

S3 (Realistic): A balanced approach where urban expansion is controlled through moderate planning measures to maintain existing ecological security while accommodating population growth.

S4 (Optimistic): Strict land-use planning and conservation policies that enhance ecological security through designated buffer zones, sustainable urban frameworks, and green infrastructure.

First scenario (S1): In this scenario, 2769 hectares of water bodies, bare lands, rangelands, and agricultural lands will be converted into residential areas. It should be noted that this is the output of the simulation done in the CA-Markov model of IDRISI software based on the trends of 2000, 2010 and 2020.

Second scenario (S2): In this pessimistic scenario, 5538 hectares of water bodies, bare lands, rangelands, and agricultural lands will be transformed into residential areas, which is about twice the size of the expansion expected in scenario S1.

Third scenario (S3): In this scenario, 1,384 hectares of bare lands and rangelands will be converted into residential areas, which is about half the size of the expansion expected in scenario S1.

Fourth scenario (S4): In this optimistic scenario, 692 hectares of bare lands will be transformed into residential areas, which is about one-fourth of the size of the expansion expected in scenario S1.

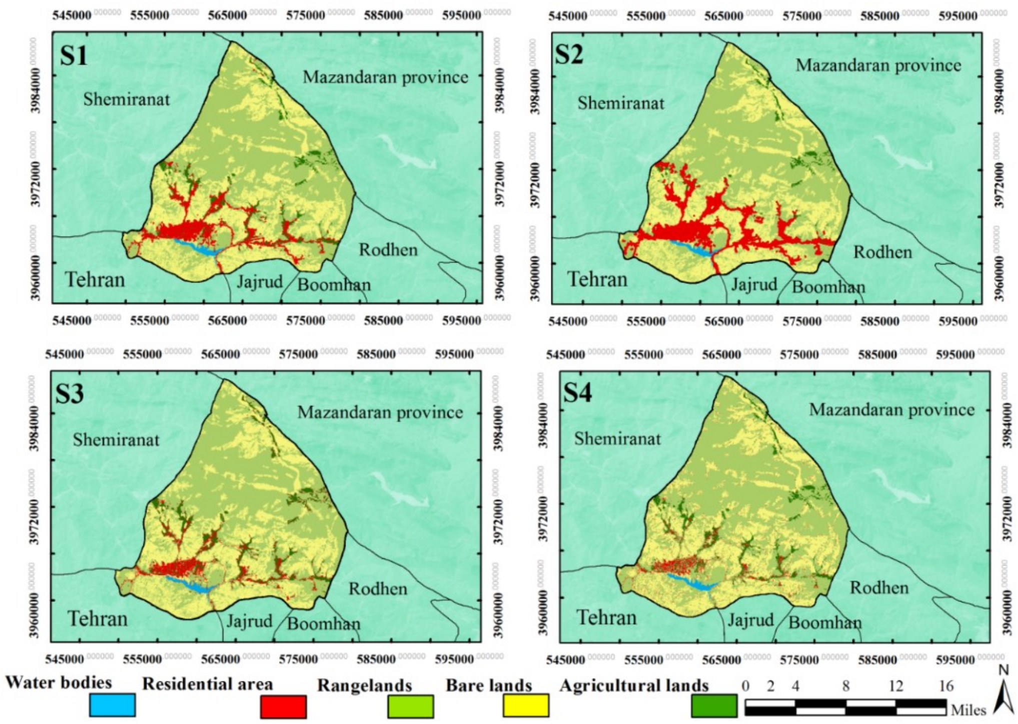

Figure 4. LULC changes by 2040 in the four scenarios

The projected changes in the area of LULC classes in the four scenarios are presented in Table 3. Among these scenarios, S2 exhibits the most substantial rangeland destruction by 2040, followed by S1, S3, and S4. In the optimistic scenario (S4), no rangeland will be converted into residential areas. On the other hand, Scenario S2 also demonstrates the lowest bare land area due to the expansion of residential areas, followed by Scenario S1. The area of these lands is greater in scenario S3 than in S4. In S4, the entire 692-hectare expansion of residential areas will occur on bare lands. In contrast, in S3, the 1384-hectare expansion of residential areas will encroach upon both rangelands and bare lands.

Table 3. Predicted changes in the area of LULC classes by 2040 in the four scenarios

land use/cover scenarios	S_1		S_2		S_3		S_4	
	Ha	%	Ha	%	Ha	%	Ha	%
Water bodies	353.6075	0.66	333.245	0.62	358.7475	0.67	358.7475	0.67
Agricultural lands	1866.49	3.52	859.5725	1.62	2231.915	4.21	2231.915	4.21
Bare lands	18277.36	34.52	17838.8925	33.7	18881.615	35.67	18323.505	34.61
Rangelands	28626.1125	54.07	27322.585	51.61	29036.0175	54.85	30286.1275	57.21
Residential area	3809.5875	7.19	6578.8625	12.42	2424.8625	4.58	1732.8625	3.27

The expansion of residential areas will be most significant in scenario S2, followed by S1, S3, and S4. Likewise, the degradation of agricultural lands will be most substantial in scenario S2, followed by S1. In scenarios S3 and S4, it is assumed that the area of agricultural lands will remain unchanged from 2020 (Fig. 5).

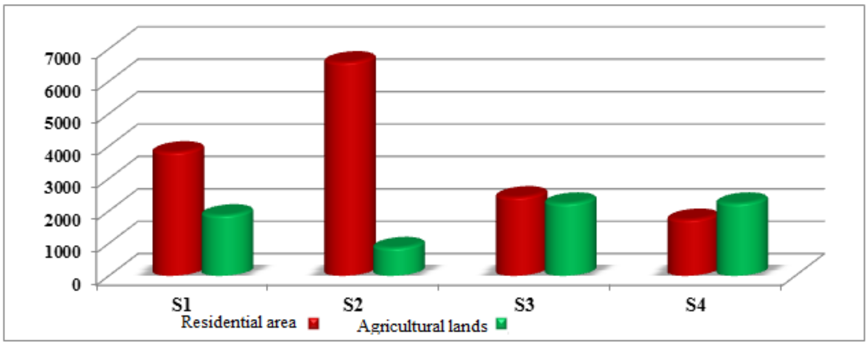

Figure 5. Comparison of changes in agricultural and residential areas in the four scenarios

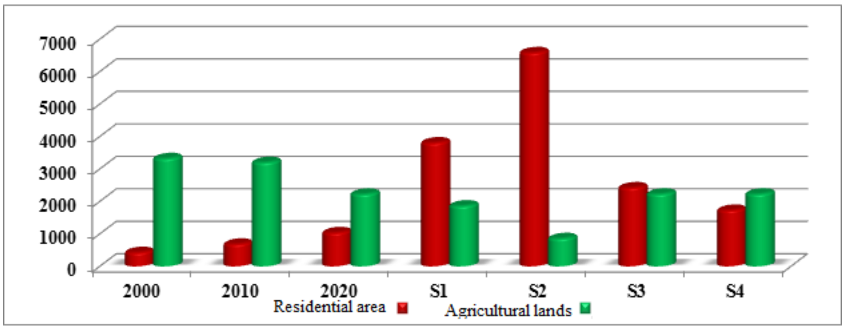

Figure 6. Comparison of changes in agricultural and residential areas from 2000 to 2040 within each scenario

Figure 6 compares the changes in the area of agricultural lands and residential areas from 2000 to 2040 within each scenario.

Water yield

The water yield model is a tool provided in InVEST 3.7.0, which has been utilized to measure water yield in numerous studies worldwide (Hu et al., 2020; Yang et al., 2019; Balist et al., 2022a; Balist et al., 2022b). To employ this model, the software requires a set of input data, including precipitation maps, potential evapotranspiration, root-restricting layer depth, plant available water content, land use-vegetation, watershed boundaries, and a biophysical table in CSV format (Hu et al., 2020) (refer to Tables 4, 5, and 6).

Table 4. The used data characteristics for water yield

Model	Type	Data	Unit	Resolution	Data of acquisition
Water yield	Spatial	Watersheds [a]	Layer.shp	30*30	2000 2010 2020
		Land use/ land cover[b]	Layer.ras		
		Root restricting layer depth[c]	(mm)		
		Plant Available Water Content	0-1		
		Precipitation[d]	(mm)		
		Average Annual Reference Evapotranspiration[d]	(mm)		

[a] National Cartographic Center- [b] These data were collected from the official website of US Geological Survey (USGS)- [C] Fao.org- [d] Worldclim.org + Meteorological Organization

Table 5. Data statistics and range of variation for InVEST model inputs

Variables (mean)	2000	2010	2020	2040(B1)	2040(N)	2040(M)
Precipitation (mm)	411.740	376.615	544.867	483.7	544/867	425/976
Evapotranspiration (mm)	2783.66	2682.62	2284.52	1466.11	2284.52	2583.201
Z	16	14	18	15	15	18
Root restricting layer depth (mm)	0-14400					

Table 6. Biophysical table used for the baseline InVEST water yield model

Lucode	LULC_desc	LULC_vegatatio[a]	Root_depth (mm)	plant evapotranspiration coefficient Kc[b]
1	Water bodies	0	-	1
2	Agricultural lands	1	1500	0.65
3	Bare lands	0	-	0.5
4	Rangelands	1	350	0.8
5	Residential area	0	-	0

[a] The values 1 and 0 indicate vegetated LC and all other LC, respectively
[b] Estimate of plant evapotranspiration for LC

Water yield in 2000, 2010, and 2020: This section presents the results of modeling water yield services in the Lavasanat watershed for different decades. According to these findings, the water yield in the entire Lavasanat watershed was 2,641,734.816 m3 in 2000, 3,318,950.915 m3 in 2010, and 7,737,201.215 m3 in 2020. Of this total water yield, 1,677,926.367 m3 in 2000, 2,287,145.055 m3 in 2010, and 4,908,786.651 m3 in 2020 belonged to residential areas. This is in contrast to the total area of residential areas in the watershed, which measured 4,820,578.505 m2 in 2000, 6,885,513.787 m2 in 2010, and 10,407,948.705 m2 in 2020 (Figure 7).

Prediction of water yield in 2040 under the defined LULC and climate scenarios: After determining the water yield for the years 2000, 2010, and 2020, the Water Yield model was employed to project the water yield for the entire watershed and its residential areas in the four land-use scenarios, which encompass existing conditions (S1), pessimistic (S2), realistic (S3), and optimistic (S4), under three climate scenarios (B1, N, and M) (refer to Figures 8, 9, and 10).

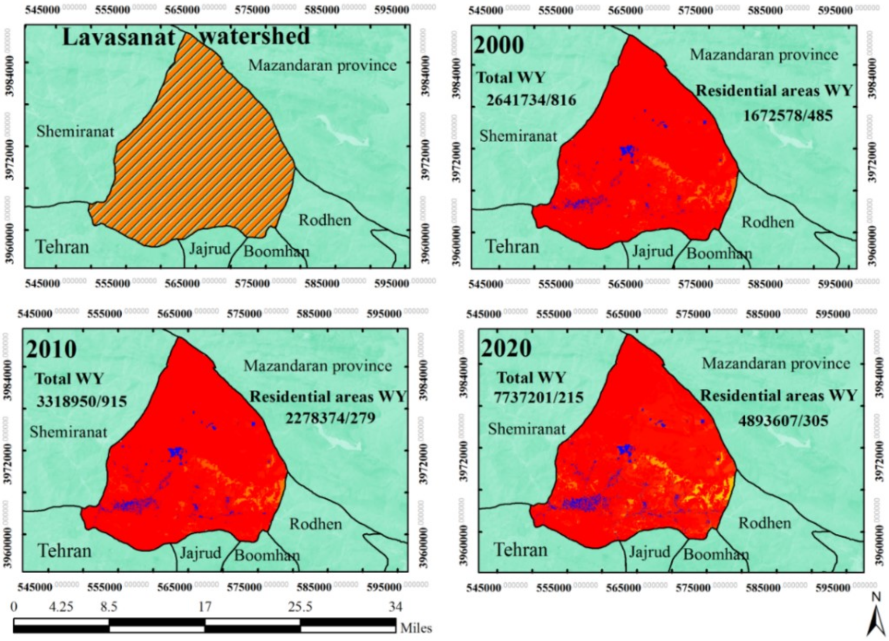

Figure 7. Water yield in 2000, 2010 and 2020

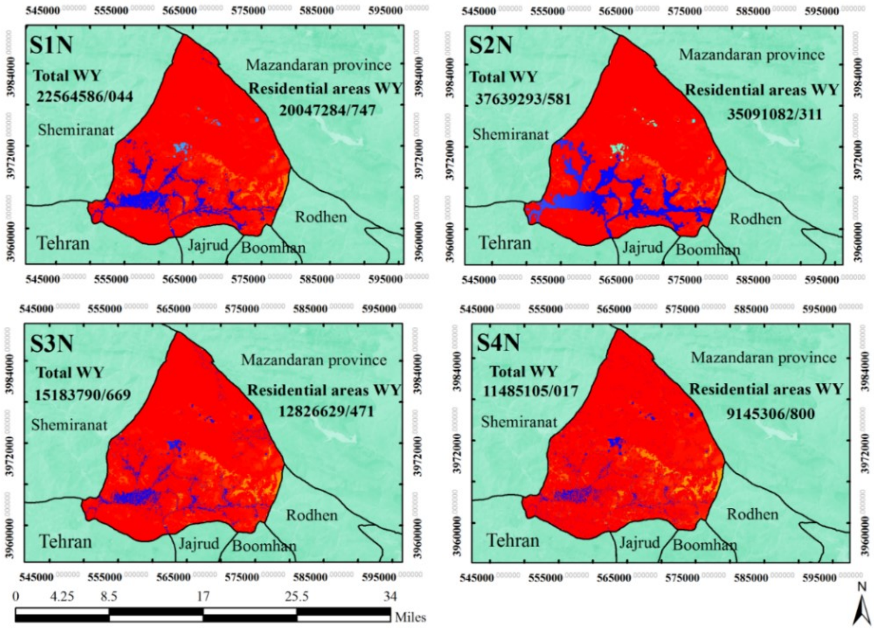

Figure 8. Water yield of the entire watershed and its residential areas in different land-use scenarios under climate scenario N

The results indicate that in the four LULC scenarios, which include existing conditions (S1), pessimistic (S2), realistic (S3), and optimistic (S4), the area of residential areas will be 38,078,250 m2, 65,712,850 m2, 24,207,400 m2, and 17,261,550 m2, respectively. Furthermore, the water yield from residential areas under climate scenario M will be 16,143,121.774 m3, 27,965,811.851 m3, 10,311,747.215 m3, and 7,353,006.022 m3, respectively. As can be observed, with changes in the area of residential areas, a key structural component of the Lavasanat watershed, their function has also evolved. The results also indicate more favorable ecological functions in scenarios S3 and S4, where it is assumed that land-use planners will take an active role in urban development management to control urban structures and conserve ecologically valuable lands, compared to the other scenarios.

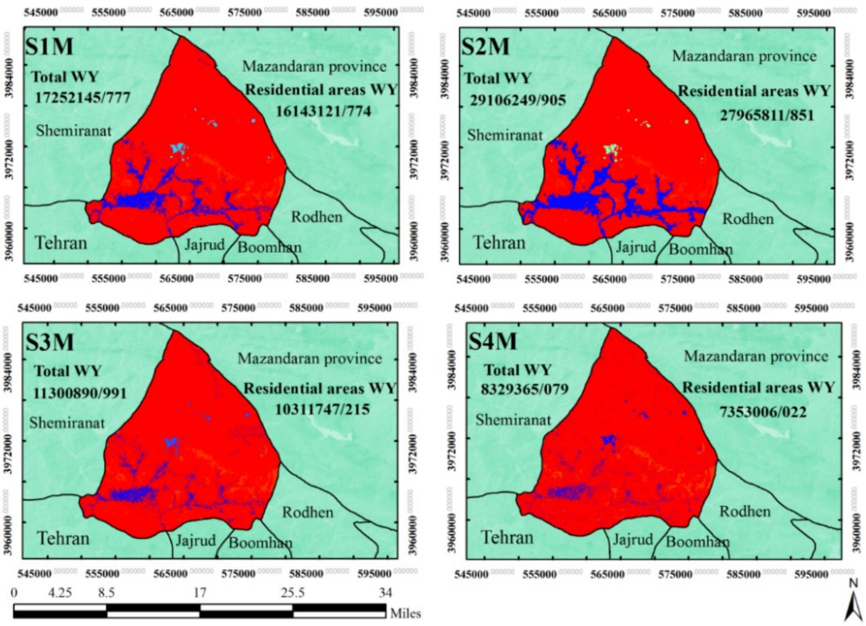

Figure 9. Water yield of the entire watershed and its residential areas in different LULC scenarios under climate scenario M

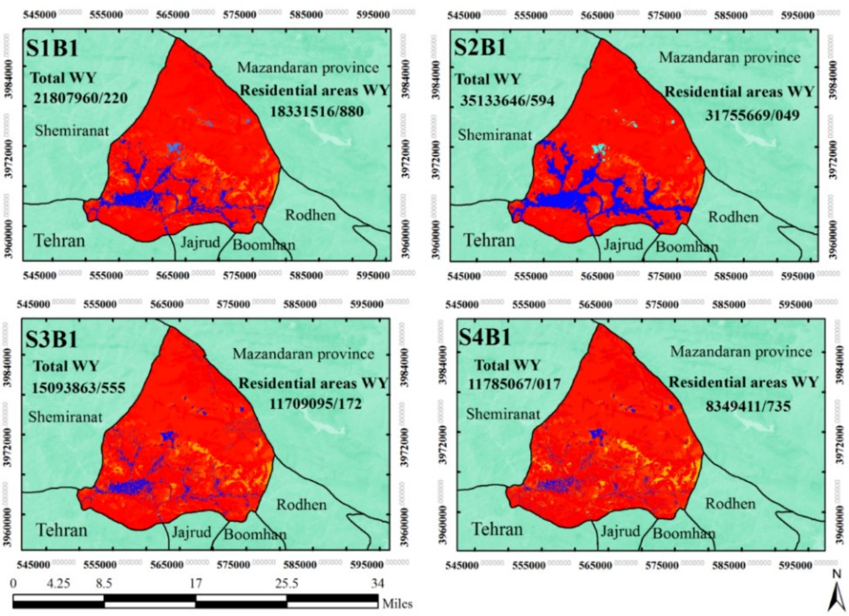

Figure 10. Water yield of the entire watershed and its residential areas in different LULC scenarios under climate scenario B1

In Table 7, a comparison is provided between the water yield of the entire watershed and that of its residential areas under different land-use/cover and climate scenarios. Based on the data in Table 7, it can be concluded that the most favorable

scenario for reducing water yield is S4M. This scenario represents optimistic land-use management involving urban development with an emphasis on improving ecological security under the climate change scenario that follows long-term climatic conditions.
The scenario with the highest water yield is S2N, representing pessimistic land-use management (urban development with a severe decline in ecological security) and the climate change scenario based on the climatic conditions of 2020.
Changes in water yield have significant ecological implications for hydrological balance, groundwater recharge, and habitat stability. Higher water yield in the pessimistic scenario (S2) results from increased impervious surfaces, leading to higher runoff, flood risks, and reduced infiltration. In contrast, the optimistic scenario (S4) promotes water retention through vegetative cover, enhancing soil moisture and biodiversity. Integrating land-use planning with water resource management is essential to mitigate adverse ecological impact.

Table 7. Changes in water yield in Lavasanat watershed in the defined scenarios

Scenarios		Climate					
		Scenario (N)		Scenario (M)		Scenario (B1)	
Water yield (M^3)		Total watershed	Residential area	Total watershed	Residential area	Total watershed	Residential area
Land-use	Scenario (S1)	22564586.044	20047284.747	17252145.777	16143121.774	21807960.220	18331516.880
	Scenario (S2)	37639293.581	35091082.311	29106249.905	27965811.851	35133646.594	31755669.049
	Scenario (S3)	15183790.669	12826629.471	11300890.991	10311747.215	15093863.555	11709095.172
	Scenario (S4)	11485105.017	9145306.800	8329365.079	7353006.022	11785067.017	8349411.735

Discussion

Changes in LULC and ecological security:

The changes in land use/cover within the Lavasanat watershed due to the expansion of residential and man-made areas represent one of the many anthropogenic factors affecting the ecosystem services of this watershed. Land-use planning can impact ecological security in two dimensions: ecological functions and structure. Land use planning not only mitigates the impact of human activities by preserving the integrity and sustainability of the landscape based on ecological principles, a fundamental requirement of urban ecological security, but also optimizes human activities considering resource constraints and ecological carrying capacity. This approach helps maintain urban functions (ecosystem services), which are also essential for urban ecological security. Hence, the ecological security of an urban area can be preserved, maintained, and enhanced through sound land use planning that takes into account ecological security patterns.

In this study, water yield does not strictly refer to surface runoff alone but rather to the total water output from the watershed, which includes both surface runoff and groundwater recharge after accounting for evapotranspiration and infiltration. Water yield is directly influenced by LULC changes, as different land-cover types regulate water retention, infiltration capacity, and runoff generation.

The results of this study substantiate this relationship. In the realistic scenario (S3), where residential expansion is limited to bare lands and rangelands, water yield across the watershed under climate scenarios N, M, and B1 was 15,183,790.669 m³, 11,300,890.991 m³, and 15,093,863.555 m³, respectively. However, in the pessimistic scenario (S2), where residential areas expand uncontrollably into ecologically valuable lands, water yield increased significantly, reaching 37,639,293.581 m³, 29,106,249.905 m³, and 35,133,646.594 m³, respectively, under the same climate scenarios.

This variation highlights how LULC changes alter watershed hydrology. Increased urban expansion with impervious surfaces (e.g., roads, buildings) reduces infiltration rates, leading to higher surface runoff volumes and lower groundwater recharge. In contrast, conservation of rangelands and vegetated areas promotes higher infiltration, reducing runoff fluctuations. These findings align with previous studies (Hu et al., 2008; Costanza et al., 2014; De Marco & Coelho, 2004; Bryan, 2013), which demonstrate that the impact of LULC changes on ecosystem services is time- and location-dependent.

Moreover, within residential areas, water yield follows the same trend. In Scenario S3, under climate scenarios N, M, and B1, water yield from residential areas was 12,826,629.471 m³, 10,311,747.215 m³, and 11,709,095.172 m³, respectively. However, in Scenario S2, these values significantly increased to 35,091,082.311 m³, 27,965,811.851 m³, and 31,755,669.049 m³, respectively. This confirms that uncontrolled urban expansion contributes to increased surface runoff, while strategic land-use planning can regulate hydrological processes and enhance ecological security.

These findings support conclusions from previous studies (Li et al., 2007; Haines-Young et al., 2012; Kindu et al., 2016; Wu, 2020), reinforcing that anthropogenic land-use changes alter ecosystem services, affecting hydrological balance and long-term ecological security. Proper land-use planning is, therefore, essential to minimise environmental damage and regulate water-related ecosystem functions in urbanising watersheds.

Ecosystem services and ecological security

Indicators such as ecosystem services play a crucial role in the functional assessment of watershed ecological security. In the case of the Lavasanat watershed, it is essential to analyze the needs of both citizens and the ecosystem to determine how citizens can benefit from ecosystem services in various dimensions.

Water yield and runoff are related but not identical concepts. Water yield refers to the total amount of water available in a watershed, including both surface runoff and groundwater recharge, after accounting for losses due to evapotranspiration and soil infiltration. In contrast, runoff specifically refers to the portion of water that flows over the land surface, moving towards streams, rivers, or other water bodies.

Since water yield is a key indicator of ecosystem services (Brisbane, 2007) and is influenced by natural, economic, and human activities (Sun et al., 2016; Yang et al., 2016; Jie et al., 2015; Liquete et al., 2011), this study employed it to assess the ecological security of the Lavasanat watershed. The inclusion of water yield as an indicator allows for a comprehensive evaluation of water resource availability in response to land-use changes and climate variability .

The results of modeling water yield services in Lavasanat watershed over different decades indicate an increase in water yield due to land use changes driven by human activities. The water yield from the watershed's residential areas increased by 36% from 2000 to 2010, by 114% from 2010 to 2020, and is projected to increase by 192% over the next 20 years.

Similarly, the watershed's residential areas expanded by 42% from 2000 to 2010, 51% from 2010 to 2020, and are projected to grow by 115% in the next 20 years. These findings align with numerous other studies that emphasize the impact of human activities and residential area expansion on water resource volume and availability (Smith, 1997; Chen et al., 2016; Yang et al., 2016; Sun et al., 2016; Liu et al., 2017). The analyses in this study reveal that the watershed's water yield increased by 25% from 2000 to 2010, 133% from 2010 to 2020, and is projected to rise by 192% over the next 20 years. The findings also indicate that climate conditions will exert a significant influence on water yield. For instance, the increased precipitation in the year 2020 had a significant impact on that year's water yield. This finding aligns with numerous other studies that highlight the importance of precipitation in influencing the water yield model (Balist et al., 2022a; Balist et al., 2022b; Kim and Jung, 2020; Yin et al. 2020; Rahimi et al., 2020; Boithias et al., 2014; Terrado et al., 2014).

In summary, climatic factors, with precipitation being the most significant, exert a substantial influence on water yield at the watershed level. However, it's essential to recognize the role of vegetation cover type and quantity in affecting water yield. Given the importance of ensuring a dependable water supply for the local population, this model can provide a reasonably accurate estimate of water yield and the contribution of vegetation to replenishing the area's underground aquifers.

The results of all four land-use scenarios under all three climate scenarios in relation to ecosystem services (water yield) showed an increase in the water yield of the watershed's residential areas and a loss of its ecologically valuable lands. Among the scenarios, S2N had the worst-case scenario for Lavasanat watershed with a water yield of 581,392.93 m3 in the entire watershed and 311,350.91 m3 in the residential areas. The next worst scenarios were S2B1, with a water yield of 594,336.46 m3 in the entire watershed and 317,556.69 m3 in the residential areas, and S2M, with a water yield of 905,062.49 m3 in the entire watershed and 851,658.11 m3 in the residential areas.

Among the scenarios with the lowest water yields, the best was S4M with a water yield of 8,329,365.079 m3 in the entire watershed and 7,353,006.022 m3 in the residential areas. The next best scenarios were S3M, with a water yield of 9,911,300.890 m3 in the entire watershed and 215,103.11747 m3 in the residential areas, and S4N, with a water yield of 11,485,105.017 m3 in the entire watershed and 9,145,306.800 m3 in residential areas.

Uncertainties and Limitations of the Modelling Approach

Despite the robustness of this approach, certain limitations exist. The CA-Markov model assumes historical land-use trends will continue, potentially overlooking socio-economic and policy changes. LARS-WG5 downscales climate data but may not fully capture long-term variability or extreme events. The InVEST model estimates total water availability but does not explicitly simulate surface runoff. Addressing these uncertainties through multi-model comparisons would enhance projection reliability.

Strengthening Policy Recommendations on Urban Planning

To mitigate the ecological impacts of urbanisation, urban planning policies must integrate nature-based solutions such as green infrastructure, permeable surfaces, and ecological buffer zones. Strategic zoning should preserve high-value ecological areas while promoting sustainable urban expansion. Coordinated efforts between planners, environmental regulators, and water resource managers are crucial for translating findings into actionable policies

In conclusion, the results demonstrate a reduction in the watershed's ecosystem services, particularly in water yield, over the 40-year period, even in the most optimistic scenarios. This decline highlights a consistent decrease in the watershed's ecological security. It's important to note that this decline occurs in the context of increasing demand for natural resources and ecosystem services in urban areas, as observed in studies by Ayres and Van Den Bergh (2005), Guo et al. (2010), and Krausmann et al. (2009).

Conclusion

The ongoing urban development characterized by the scattered expansion of residential areas in the Lavasanat watershed is poised to have detrimental consequences for the region's environment, natural resources, as well as the health, social, and economic well-being of its residents. If the current trends persist (scenario S1) or worsen (scenario S2), it is anticipated that by 2040, there will be a significant reduction in the area of agricultural lands, orchards, rangelands, and bare lands within the watershed. This will result in the rapid degradation of its ecosystems and habitats, leading to a decline in air and water quality. Ultimately, these environmental changes are expected to have adverse effects on the well-being and quality of life for the area's citizens.

In essence, urbanization, being the primary driver of land use and land cover changes, will fundamentally alter the landscape patterns and the structures and functions of the urban ecosystem within the watershed. The extensive urbanization and the unregulated expansion of residential areas in the region are responsible for a range of environmental issues. These issues include landscape fragmentation, heightened runoff, increased soil erosion, loss of plant and animal species, as well as water, soil, and air pollution. These problems arise from the rapid urbanization of the area without due consideration for the ecological and environmental value of the lands being transformed.

In their assessment of the United Nations' sustainable cities program, Rasoolimanesh et al. (2011) emphasized a crucial aspect of sustainable urban development, which is the preservation and utilization of a city's green spaces, natural resources, and infrastructure. Therefore, to attain sustainable development in Lavasanat watershed, it's imperative to enhance the region's social and economic frameworks without causing harm to its natural environment.

As stated by Huseynov (2011), the effectiveness of sustainable urban planning is closely tied to the rejuvenation and enhancement of natural resources and infrastructure, as well as the establishment of green urban infrastructures. These measures have the potential to enhance the urban environment's quality and play a pivotal role in instigating significant transformations within cities. Hence, one approach to enhancing land-use planning and green urban infrastructure in Lavasanat watershed is the establishment of ecological security patterns.

Ecological security stands as a paramount facet of environmental preservation, and its preservation holds a pivotal role in humanity's pursuit of sustainable development in the 21st century. Su et al. (2016) and Opdam et al. (2006) have highlighted the significance of constructing ecological security patterns as a potent strategy for safeguarding the natural functions, upholding ecological security, and achieving equilibrium between economic progress and ecological soundness within a watershed. Consequently, for Lavasanat watershed, land-use planning that takes into account ecological security criteria will be of utmost importance in upholding the ecological security of the watershed's urban areas. In essence, sound land-use planning will enhance the watershed's ecological security by preserving the equilibrium between its ecological functions and structures.

The results of this study also affirm that the ecological security of cities can be enhanced through effective land use planning. For instance, in the scenario of maintaining current conditions (S1), the water yield for the entire watershed under climatic scenarios N, M, and B1 was 22,564,586.044 m3, 17,252,145.777 m3, and 21,807,960.220 m3, respectively. In the optimistic scenario (S4), these figures decreased to 11,485,105.017 m3, 8,329,365.079 m3, and 11,785,067.017 m3, respectively. Similarly, in the scenario of existing conditions (S1), the water yield for the watershed's residential areas under the climate scenarios N, M, and B1 was 20,047,284.747 m3, 16,143,121.774 m3, and 18,331,516.880 m3, respectively. In the optimistic scenario (S4), these figures decreased to 9,145,306.800 m3, 7,353,006.022 m3, and 8,349,411.735 m3, respectively. These numbers clearly illustrate the influence of land-use changes, particularly the expansion of residential areas, on the ecosystem services. All the results presented in this paper, along with others, emphasize that maintaining and improving ecological security for sustainable urban development can be achieved through proper land-use planning.

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