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Spatial–temporal assessment and modeling of ecological security based on land-use/cover changes (case study: Lavasanat watershed)

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Abstract

Spatial–temporal land-use changes can greatly influence ecosystem services and landscape patterns, which themselves are important factors of ecological security. Spatial–temporal land-use changes can greatly influence ecosystem services and landscape patterns, which themselves are important factors of ecological security. This study analyzed the spatial–temporal changes of land-use/cover in the Lavasanat watershed (Tehran, Iran) between 2000 and 2020 using Landsat satellite images and evaluated the ecological security of the region in terms of landscape metrics and ecosystem services. The spatial–temporal analysis of land-use changes in the 20-year period between 2000 and 2020 showed the substantial growth of the region's residential areas because of population growth and rising demand for housing and the consequent urban expansion. This analysis also showed a decreasing trend in the total area of agricultural lands in the region. The results suggest that uncontrolled real estate development has greatly affected the ecological structure of the Lavasanat region by breaking the continuity of agricultural lands and replacing the large patches of these lands, which are of great ecological value, with smaller patches, which have far lower ecological value. Also, the results of the InVEST scenario-generator model and the water yield model showed an increase in the water yield of the Lavasanat watershed because of the expansion of built (residential) land-uses, which has led to increased runoff. These changes will have significant environmental consequences such as increased soil erosion, reduced regional groundwater recharge, and easier contaminant displacement, which will undermine the ecological security of the region.

Keywords Ecosystem services · Landscape patterns · Landscape metrics · Water yield

Introduction

Although a small percentage of the world's land surface is covered with urban areas, these areas are the primary source of most of the world's environmental issues, including carbon emissions, energy and resource overuse, and biodiversity and ecosystem degradation (Grimm et al. 2015; Mcdonald et al. 2008; Seto et al. 2012). Indeed, the poorly planned and controlled expansion of urban structures in combination with the shrinking of ecologically valuable landscapes is making urban development unsustainable (Peng et al. 2017; Feist et al. 2017). As a result, finding a way to ensure the structural stability and functional security

of natural ecosystems for sustainable urban development has become a global challenge (Cumming and Allen 2017). The structural and functional changes caused by uncontrolled urban expansion can undermine the ecosystem services (ESs) provided by the ecological infrastructure and threaten the cities' environmental security and sustainable development. Therefore, to preserve the ecological security of cities, urban planners and administrators are always looking for urban planning measures and methods that can help them regulate and control urban structure in support of the stability of ecosystem functions (Zhaoxue and Linyu 2010: 1394).

One major way to preserve sustainability in urbanizing landscapes is to create a landscape ecological security pattern in order to effectively protect ecological security by managing the interactions between landscape patterns and ecological processes (Wu et al. 2013; Yu et al. 2006). The ecological security approach has emerged as an effective instrument for the fundamental assessment of ecosystem structures and functions that are threatened by urban expansion and economic development

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(Solovjova 1999; Kullenberg 2002; Ma et al. 2004; Eckersley 2005) and thus a powerful tool for protecting the ecological security of regional ecosystems (Su et al. 2013; Berkes and Folke 1998; Haeuber and Ringold 1998; Devuyst et al. 2001; Ehrlich 2002).

The concept of landscape ecological security pattern was introduced by Yu (1996), who believed that protecting ecological security could be the most useful approach for preserving ecologically valuable processes and landscape patterns (Yu 1995, 1996). According to Yu, ecological security patterns can preserve the structural integrity, functions and processes of an ecosystem (Zhang et al. 2015). Ecological security patterns can serve as a potent tool for protecting regional ecological security by preserving the important parts of the landscape and important ecological processes (Yu 1996; Kattel et al. 2013; Peng et al. 2018a). From the perspective of landscape ecology and the interaction between landscape patterns and ecological processes, creating and optimizing ecological security patterns can help prevent poor landscape protection, manage the conflict between environmental protection and economic development, and preserve the ESs that are needed in a healthy environment (Yu 1996; Kattel et al. 2013). Research into ecological security patterns can be conducted at the city (Peng et al. 2019), province (Peng et al. 2018b), region (Zhang et al. 2017), country (MacMillan et al. 2007), or even global scales.

Indicators of ecological security play a key role in the assessment of this quality. It should also be noted that different ecosystems need their own unique indicators in different temporal and spatial dimensions (Zhao et al. 2006). One of the indicators of ecological security is the quality of ESs (Chen et al. 2018) and landscape patterns (Liu and Chang 2015). In recent years, many countries have started to pay more attention to research on ESs and landscape patterns with an ecological security approach (Gao et al. 2012; Zhang et al. 2016; Liu et al. 2018; Chen et al. 2018; Ma et al. 2019) and using the findings as a basis for decision-making about preserving socioeconomic balance as well as ecosystems (Chen et al. 2018).

Ecological security of the earth has been a major source of concern for governments as well as academia since the late 1970s (Bächler et al. 1995; Matthew et al. 2002). Over the years, this issue has received increasing attention (Peng et al. 2019; Wang et al. 2019; Liu et al. 2018) and has been the subject of many studies across the world (Zhang et al. 2017; Yang et al. 2018; Li et al. 2019a, b; Yang and Cai 2020; Li et al. 2020). Also, various tools have been developed for measuring this security. But given the complexity of this subject, there is still ample room and ongoing efforts for advancement in this field and the aforementioned tools. Of the numerous studies conducted in this field, many have assessed the current ecological security (Zhang et al. 2017; Li et al. 2020), some have only focused on ecological landscape issues (Liu et al. 2018; Ma et al. 2019), and some have attempted to make a connection between ecological security and ecological footprint (Yang and Cai 2020; Hao et al. 2017). Also,

many of these studies have evaluated the ecological security of a landscape in the past as well as the present (Li et al. 2019a; Wang et al. 2019; Wu et al. 2019), some have also discussed the issues concerning ESs and ecological security (Qin et al. 2019; Pasgaard et al. 2017), and others have focused on the past ecological security of a region (Lu et al. 2020; Chen et al. 2020).

This study presents a spatial–temporal analysis of land-use/cover changes and their ecological effects in a region using InVEST 3.7.0 and FRAGSTATS 4.2.1 models. These analyses are meant to provide, through the assessment of ecological security with a comprehensive approach to landscape ecology and ESs, the scientific information that might benefit the management and monitoring of the Lavasanat watershed in Tehran, Iran. Today, one of the major challenges in this watershed is the trend of land-use change, which can be attributed to the encroachment of the Tehran metropolitan area into nearby natural and agricultural lands especially since 2000. These land-use changes have resulted in the expansion of previously built areas in the form of fast urbanization, and also the emergence of new residential areas in the Lavasanat region, which highlight the need to address the issue to prevent further damage.

In particular, the objectives of the present study are as follows:

1. Spatial–temporal analysis of LULC changes from 2000 to 2020
2. Analysis of changes in landscape metrics and ESs (water yield) in response to LULC changes
3. Analysis of changes in ecological security due to LULC changes from 2000 to 2020 in terms of landscape metrics and ESs (water yield).

Materials and methods

Study area

This research has been performed in the Lavasanat catchment, which is located in Shemiranat County of Tehran province (Fig. 1). The area of this catchment is 52933 hectares, and its inhabitants are 25,000 people. The city of Lavasan is the largest residential area in this catchment. Stretched between 51° 24′ and 51° 50′ east longitudes and 35° 46′–36° 03′ north latitudes, Lavasanat watershed is bound on the north by the Noor county, on the west by the Karaj county, on the east by the Damavand county, and on the south by the city of Tehran (Rahmani Fazli et al. 2017). Lavasanat watershed consists of three sub-watersheds called Kond, Afjeh, and Lavarak, and its main rivers and tributaries discharge directly into the Latyan Dam reservoir (Talari 2016).
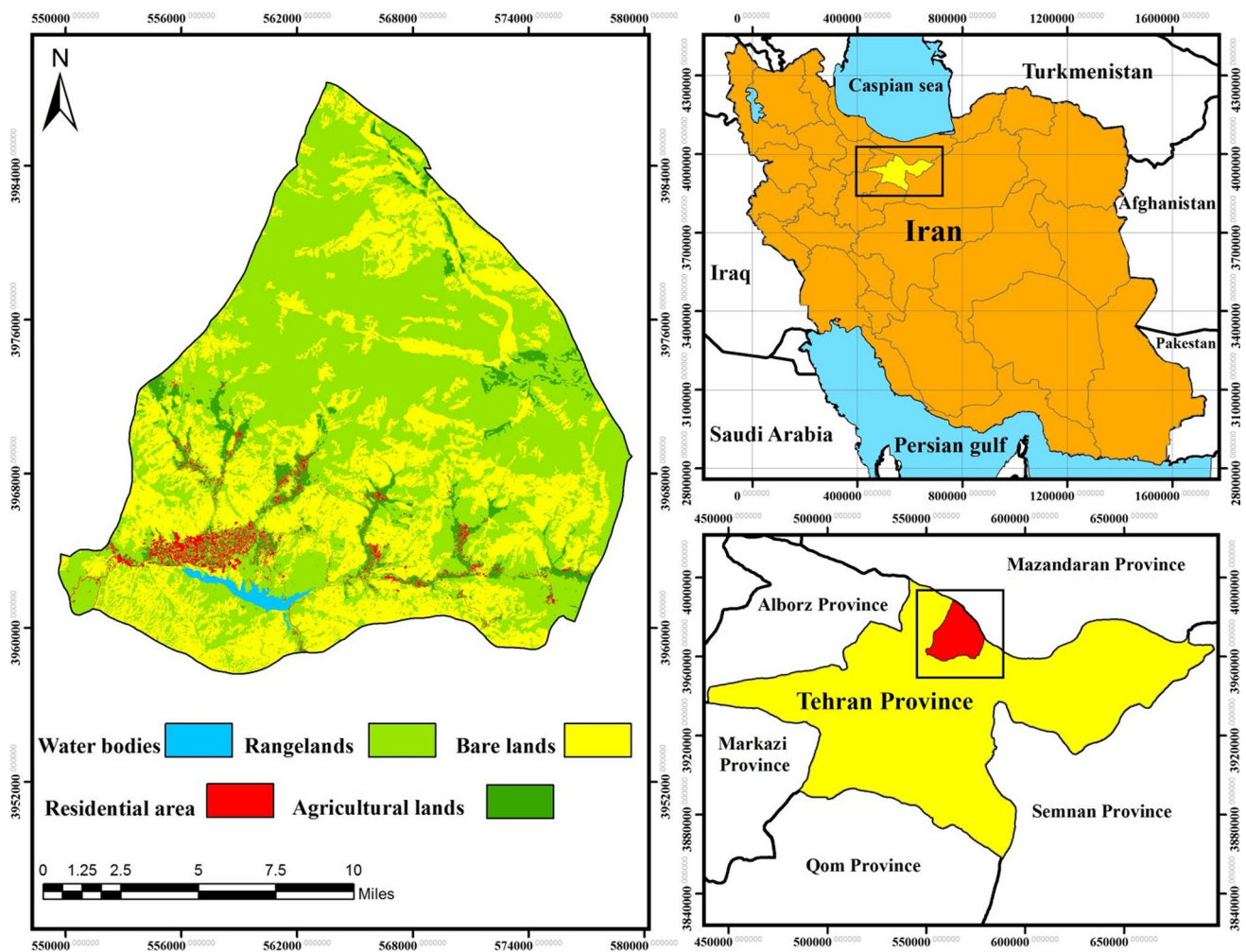
Fig. 1 Location and land-use classes of the Lavasanat

Methodology

In this study, first, a spatial–temporal analysis was conducted on LULC changes in the study area, and then, the InVEST 3.7.0 and FRAGSTATS 4.2.1 models were used to assess these land-use changes, and finally, an analysis was performed to determine changes in the region's ecological security in terms of landscape metrics and ESs (water yield) (Fig. 2).

Spatial–temporal analysis of land-use/cover changes

LULC images for the 20-year period of interest (2000, 2010, and 2020) were prepared using two sets of data. Initially, the authors intended to only use Landsat satellite images (Table 1). However, since many parts of the study area contained patches of land-uses in low-density villages and also many land-uses were too close to be distinguished in Landsat satellite images, for such areas, manually made land-use maps were digitized using high-resolution spatial images of the area. Ultimately, the results of the two methods were merged to create a coherent LULC map for the period of interest.

To fix some errors in the images, they were subjected to a pre-processing, which involved either geometric or atmospheric correction depending on the image classification. The radiometric correction was performed on multi-time images, i.e., images taken at different seasons or years or by different sensors (Du et al. 2002). Before being used in digital analysis, satellite data were examined to ensure standard quality in terms of geometric or radiometric errors such as stripe noises, misaligned scan lines, and duplicate pixels, and atmospheric errors such as cloudy spots.

The geometric correction was conducted by the use of cadastral maps, visual interpretation, Google Earth, and field trips. Since satellite images were in raster format and the pixel rows and columns in these images were not aligned with terrestrial coordinates, for georeferencing, the digital data of an acceptable number of points with appropriate distribution had
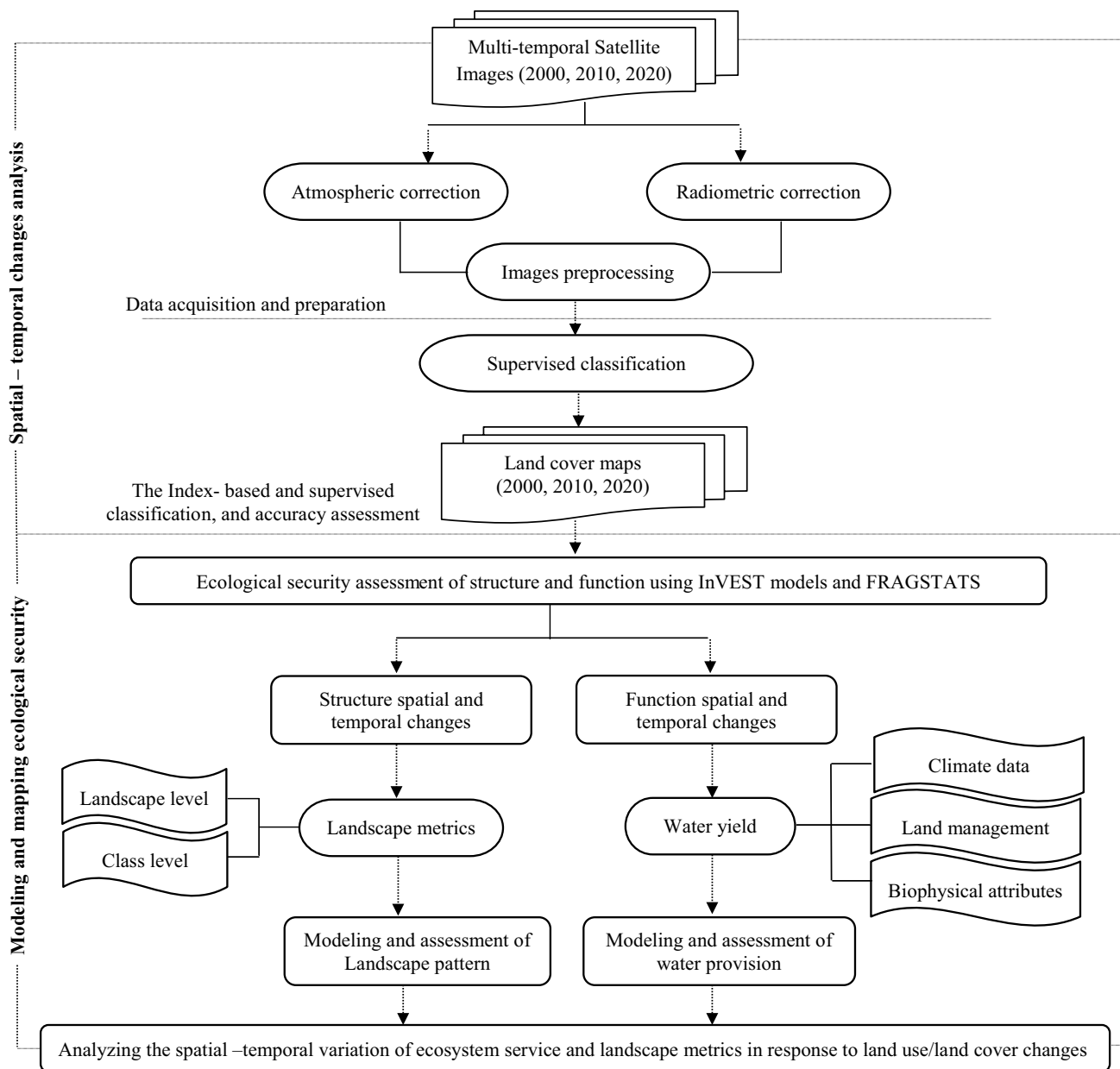
Fig. 2 Schematic diagram for mapping and modeling ecological security

Table 1 Description of satellite images

Characteristics	Resolution/sensor	Path/row	Resolution pan-chromatic	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)

to be extracted from the images. Therefore, the data of 20 ground control points were extracted from the 1:25,000 digital maps and used in the geometric correction. These points were selected so that they would cover the entire area and would be detectable on the ground and clearly visible on the image. Then, the regression method in the software ENVI5.3 was used to transfer the DN1 values of pixels from the original image to the created image and perform the geometric correction. In this process, while selecting the RMS2 values (root mean square error), the authors tried to use those with RMS < 1.

In view of the land-uses present in the region, the research objectives, and the spatial and radiometric resolution of the images, the lands were classified into five lands-uses, including residential areas (urban, rural, and industrial areas and roads), bare lands, rangelands, water bodies, and agricultural lands, using the supervised classification method called maximum likelihood in ENVI5.3. After this process, the accuracy of the classification was evaluated by two measures: overall accuracy (OA) and kappa coefficient (KC).

Spatial–temporal changes assessment

Landscape patterns metrics

Considering the research objectives and the studies previously conducted in this field, and also the overlap between some metrics, this study used six metrics at the class and landscape level (Table 2). Landscape patterns were calculated using FRAGSTATS 4.2.1(McGarigal et al. 2012).

Assessment of ecosystem services

LULC changes due to the expansion of residential and other built areas as well as agriculture are among the most important human factors that affect ecosystem services (Li et al. 2007). One of the most valuable ecosystem services is water yield (Brisbane 2007), which happens to be more vulnerable than other ecosystem services to severe land-use changes (Tao et al. 2016). Typically defined for dry ecosystems (Brauman et al. 2007), this ecosystem service depends on watershed characteristics such as topography, vegetation cover, land-use, climate and other parameters (De Groot et al. 2010). Therefore, measuring changes in the water yield ecosystem service in response to land-use change is an effective way to assess the environmental costs and benefits of land-use planning. Thus, modeling the ecosystem services (water yield) of a watershed can help governments to monitor and predict the effect of economic development policies and the consequent land-use changes and adopt proper plans and policies accordingly (Lang et al. 2017).

Modeling and simulation

InVEST modeling

The water yield (WY) in the Lavasanat watershed was determined using the WY model in the software InVEST3.7.0. This model predicts and demonstrates how changes in land-use patterns affect WY and its functions in different sectors. Over the years, this tool has been used for analysis and evaluation of WY in a large number of studies and management programs across the world (Rahimi et al. 2020; Hu et al. 2020; Yang et al. 2019; Hamel and Guswa 2015; Boithias et al. 2014). The WY model of InVEST is based on the Budyko curve (Budyko 1974), which is an empirical function relating the ratio of actual evapotranspiration to the ratio of potential evapotranspiration to precipitation.

In this model, first, the mean annual water yield $Y(x)$ of each pixel of the landscape is calculated as follows (Sharp et al. 2019):

$$Y(x) = \left(1 - \frac{\mathrm{AET}(x)}{P(x)}\right) \cdot P(x) \tag{1}$$

Table 2 Landscape patterns metrics

Landscape metrics	Scale	Relevant reference
Number of Patches (NP)	Class/landscape	Rahimi et al. (2020), Yu et al. (2019), Liu et al. (2018)
Landscape Shape Index (LSI)	Class/landscape	Ma et al. (2019), Yu et al. (2019), Pan et al. (2019)
Interspersion and Juxtaposition Index (IJI)	Class/landscape	Yu et al. (2019), Liu et al. (2018)
Patch Density (PD)	Landscape	Ma et al. (2019), Li et al. (2019a; b), Wu et al. (2019)
Edge Density (ED)	Landscape	Li et al. (2019a; b), Yu et al. (2019), Kim (2019)
Splitting Index (SPLIT)	Landscape	Li et al. (2019a; b), Ma et al. (2019)
Class Area (CA)	Class	Chen et al. (2014)
Percentage of landscape (PLAND)	Class	Kim (2019), Chen et al. (2014)
Largest Patch Index (LPI)	Class	Ma et al. (2019), Yu et al. (2019), Pan et al. (2019)

where AET(x) is the mean annual actual evapotranspiration of pixel x and P(x) is the mean annual precipitation of the same pixel.

In the InVEST model, the input land-uses are divided into two classes, vegetated and non-vegetated, and the $\frac{AET(x)}{P(x)}$ ratio of each class is calculated differently. For vegetated land-uses, this ratio is calculated based on the Budyko curve of Fu (1981) and Zhang et al. (2004):

$$\frac{AET(x)}{P(x)} = 1 + \frac{PET(x)}{P(x)} - \left[1 + \left(\frac{PET(x)}{P(x)}\right)^{\omega}\right]^{1/\omega} \tag{2}$$

where PET(x) is the potential evapotranspiration of pixel x, and $\omega(x)$ is a non-physical parameter that depends on the natural climatic-soil characteristics of the pixel. Potential evapotranspiration, PET (x), is defined as follows:

$$PET(x) = K_C(l_x) \cdot ET_{\circ}(x) \tag{3}$$

In this equation, $ET_{\circ}(x)$ is a parameter reflecting the climatic conditions of the area based on the evapotranspiration of a reference plant in that area, and $K_C(l_x)$ is mainly determined by the vegetation characteristics of the land-use in the pixel (Allen et al. 1998).

$\omega(x)$ is an empirical parameter that can be expressed as a linear equation of $\frac{AWC*N}{P}$, where N is the number of events per year, and AWC is the water content available for plant use (mm). This linear equation is as follows (Donohue et al. 2012):

$$\omega(x) = Z\frac{AWC(x)}{P(x)} + 1.25 \tag{4}$$

Here, AWC(x) is the available water content (mm) in pixel x, which depends on soil texture and effective rooting depth. AWC(x) determines the amount of water that the soil retains for plant use. This parameter is obtained by multiplying the plant available water capacity (PAWC) by the root-restricting layer depth or the plant rooting depth, whichever is lower (Yang et al. 2019):

$$AWC(x) = Min(Rest \cdot layer \cdot depth, \ root \cdot depth) \cdot PAWC \tag{5}$$

The root-restricting layer depth is the depth beyond which the roots cannot penetrate into the soil because of its physical and chemical properties. The plant rooting depth is usually considered to be the depth at which 95% of the root biomass occurs. PAWC is the difference between the soil's water-holding capacity and the plant wilting point (Yang et al. 2019).

The hydrogeological parameter Z is an empirical constant between 1 and 30, which reflects the local precipitation pattern, precipitation intensity, seasonal climate change, and topographic features of the watershed. There are three methods to obtain Z (Sharp et al. 2014): (1) using the formula N×0.2, where N is the number of rainy days in a year (Donohue et al. 2012) [the

lower the number of rainy days in an area, the lower the Z value (Redhead et al. 2016)]; (2) using the global ω estimate (Liang et al. 1994; Xu et al. 2013); (3) estimation after calibration with actual runoff data (Canqiang et al. 2012).

For non-vegetated land-uses (such as urban areas, wetlands, etc.), the actual evapotranspiration AET(x) is obtained directly from the reference evapotranspiration $ET_{\circ}(x)$ using the following equation:

$$AET(x) = Min\left(K_c(l_c) \cdot ET_{\circ}(x), P(x)\right) \tag{6}$$

In this equation, $ET_{\circ}(x)$ is the reference evapotranspiration and $K_c(l_c)$ is the land-use-specific evaporation factor.

Results and discussion

Assessment of land-use/cover changes

After preparing the maps of LULC classes, the changes occurred during the study periods were examined (Fig. 3). In the validity assessment of the obtained classification, the overall accuracy and kappa coefficient of the classification for the years 2000, 2010, and 2020 were calculated to 95.72, 96.26, and 95.32 percent and 0.948, 0.943, and 0.936, respectively. These results indicated the land-use classifications are acceptably accurate and match the reality on the ground (Table 3). The classification done with the maximum likelihood algorithm showed that there are five classes of land-use in the area: residential areas (urban, rural, and industrial areas and roads), bare lands, rangelands, water bodies, and agricultural lands (Fig. 3).

The prepared land-use maps and data collected from satellite images clearly demonstrate the expansion of residential areas because of population growth and rising demand for housing and the consequent urban expansion. On the contrary, agricultural lands have shrunk over the study period. The growth of residential areas and the shrinking of agricultural lands between 2010 and 2020 are quite evident. Given the current trend of land-use change, one can expect a sharp decrease in the area of agricultural lands in the coming years. Rangelands of the watershed have shrunk between 2000 and 2010, but have grown between 2010 and 2020, a trend that can be attributed to the conversion of agricultural lands into rangelands in the second period. The area of bare lands in the watershed has decreased in both periods (Table 3).

Landscape pattern analysis at different levels

Analysis of landscape pattern at class level

(1) Changes in land-use classes in terms of CA: The total area of residential land uses in the Lavasanat watershed in 2000, 2010, and 2020 has been 432.4, 689.82, and 1040.86,
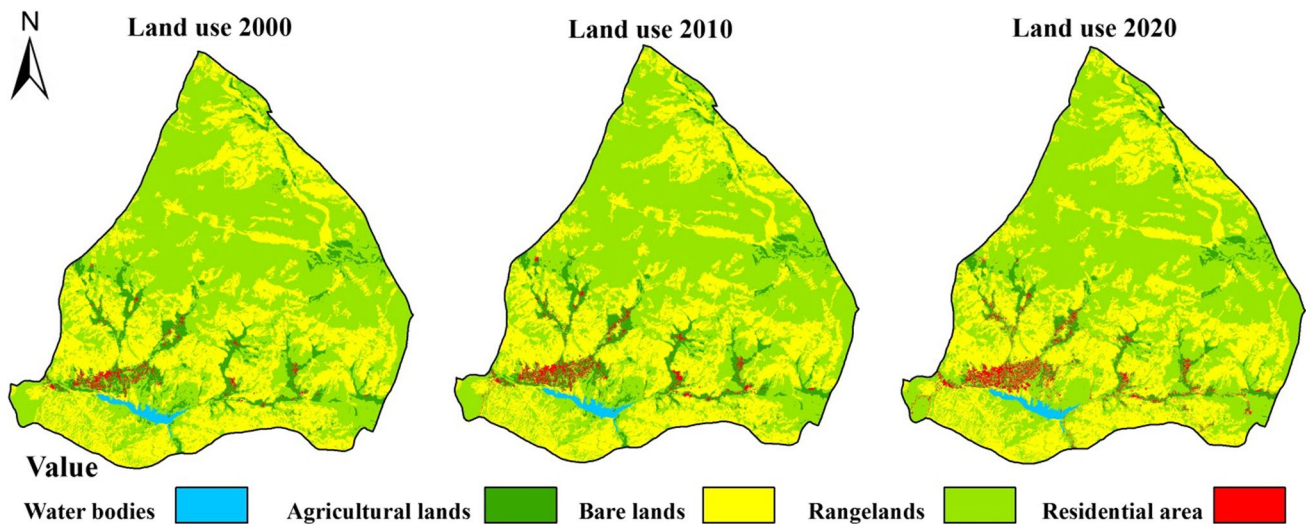
**Fig. 3** Land-use Lavasanat watershed for years 2000, 2010, and 2020

Table 3 Area statistics of LU/LC classification during the study period

Land-use/land-cover	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	19,117.362915	36.11	19,079.384967	36.04	19,015.562751	35.92
Rangelands	29,704.299642	56.11	29,601.808827	55.92	30,289.395861	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	

respectively. This increase clearly reflects the expansion of built areas in the region. The total area of bare lands in these years has decreased from 19,117.28 to 19,079.35 and ultimately to 19,015.51. In these years, the total area of agricultural lands has also decreased from 3224.36 to 3204.7 and then to 2231.91. The area of rangelands has decreased from 29,702.61 in 2000 to 29,600.46 in 2010 but has then increased to 30,286.13 in 2020 because of land-use changes (Fig. 4a—CA).

(2) Changes in land-use classes in terms of PLAND: The percentage of landscape (PLAND) covered by residential areas has increased from 0.81% in 2000 to 1.3% in 2010 and then to 1.96% in 2020. For bare lands, this metric has decreased from 36.11 to 36.04% and ultimately to 35.92%, showing the slight shrinkage of bare lands in the region. For agricultural lands, PLAND has been 6.28% in 2000, 6.5% in 2010, and 4.21 in 2020, which demonstrate an accelerating reduction. Between 2000 and 2010, the percentage of the landscape covered by rangelands has decreased from 56.11 to 55.92%, but between 2010 and 2020, this metric has bounced back up to 57.21% (Fig. 4b—PLAND).

(3) Changes in land-use classes in terms of the NP: As the results show, the NP of residential areas in 2000, 2010, and 2020 has been, respectively, 1626, 2943, and 3774, which demonstrate an increasing trend and is indicative of the growth and expansion of built areas in the landscape. The NP of agricultural lands in the same years has been, respectively, 1248, 1648, and 1842. The NP of bare lands has also had a rising trend, increasing from 113 in 2000 to 197 in 2010 and to 403 in 2020. The NP of rangelands has decreased from 10,084 in 2000 to 9861 in 2010, but shows an increasing trend between 2010 and 2020 because of land-use changes (Fig. 4c—NP).

(4) Changes in land-use classes in terms of IJI: According to the results obtained for this index, between 2000 and 2010, the IJI of residential areas has increased from 54.72 to 63.54, which means an increasing level of contact with patches of different classes. But from 2010 to 2020, the IJI of residential areas has dropped to 55.39, probably because residential areas have become more continuous and consolidated. IJI of rangelands in the years 2000, 2010, and 2020 has been, respectively, 55.39, 55.05, and 66.11, which show a slight increase in the second 10-year period.

Fig. 4 Changing trend of landscape pattern at class level
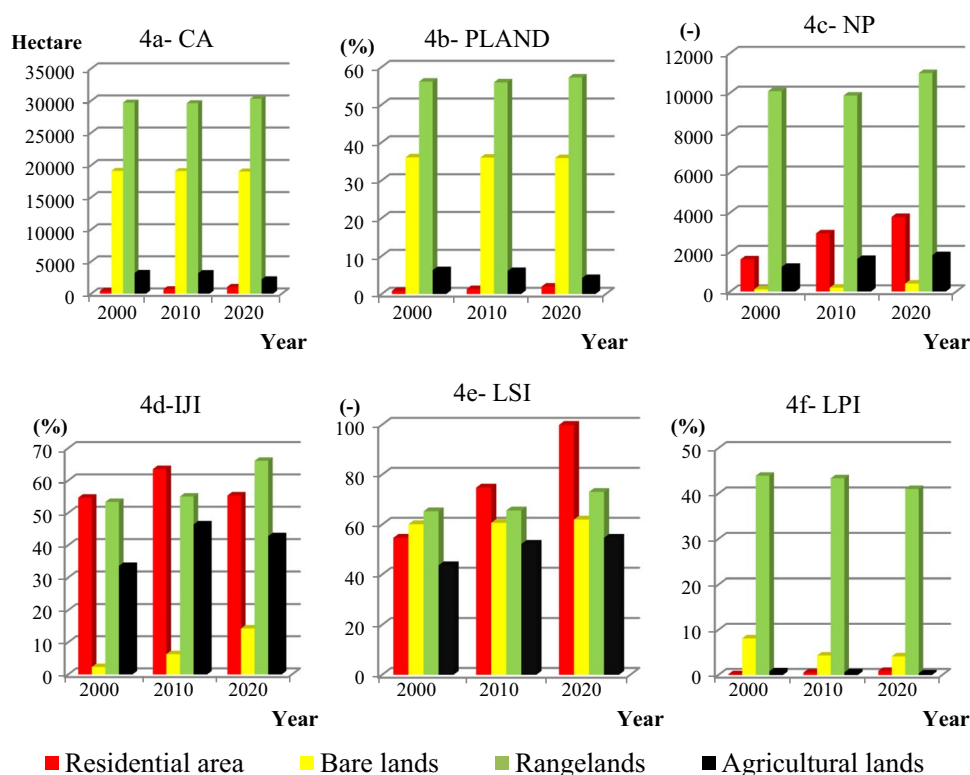
For bare lands, the metric (IJI) has been rising consistently, increased from 2.31 in 2000 to 6.3 in 2010 and then to 14.32 in 2020. For agricultural lands, IJI has increased from 33.63 in 2000 to 46.43 in 2010 but then has decreased to 42.79 in 2020 (Fig. 4d—IJI).

(5) Changes in land-use classes in terms of LSI: The LSI of residential areas in 2000, 2010, and 2020 has been, respectively, 54.72, 74.82, and 99.9, reflecting the increasingly complex and irregular shape of these land-uses. For agricultural lands, LSI has increased from 43.68 to 52.26 and then to 54.69, which signifies the fragmentation of the patches of agricultural land and consequently the increasing geometrical irregularity and complexity of these patches. The same can also be said for rangelands, for which LSI has increased from 65.3 in 2000 to 65.65 in 2010 and to 73.08 in 2020. There has also been a slight increase in the LSI of bare lands in the years 2000 (60.12), 2010 (60.66), and 2020 (62) (Fig. 4e—LSI).

(6) Changes in land-use classes in terms of LPI: For residential areas, LPI has shown a consistent trend, increasing from 0.19% in 2000 to 0.56% in 2010 and to 0.91% in 2020. For the bare lands class, this metric has decreased from 8.12% in 2000 to 4.32% in 2010 and ultimately to 4.13% in 2020. This trend can be attributed to the shrinking total area of this class and the increasing fragmentation of the patches of bare land in the watershed. Between 2000 and 2020, the LPI of agricultural lands has also decreased consistently (from 0.82 to 0.59 and then 0.36), which can be attributed

to the expansion of residential areas and the complete disappearance of the patches of farmlands. For rangelands, LPI in the years 2000, 2010, and 2020 has been 43.93, 43.37, and 41.1, respectively (Fig. 4e—LPI).

Analysis of landscape pattern at landscape level

The total NP in the entire watershed in the years 2000, 2010, and 2020 has been, respectively, 13,073, 14,651, and 17,016. This increasing trend is indicative of increased fragmentation of the landscape because of the land-use changes occurred in the watershed (Fig. 5a—NP; Table 4). PD in the landscape during the same years has been 24.69, 27.67, and 32.14, respectively, which also reflects the increase in the number of landscape patches (Fig. 5b—PD; Table 4). These trends indicate the rising trajectory of landscape fragmentation in the watershed. LSI of the Lavasanat watershed for the years 2000, 2010, and 2020 was calculated to 51.34, 54.33, and 59.72, respectively, which means the landscape is becoming increasingly complex and irregular in terms of the geometry of its land-uses (Fig. 5c—LSI; Table 4). This increased complexity has made the landscape patches unstable. In other words, the level the degradation has increased with the increasing geometrical complexity of land-uses. Thus, the increasingly irregular shape of the landscape is indicative of man-made degradation and disturbances in the Lavasanat watershed.

SPLIT of the watershed for the years 2000, 2010, and 2020 was calculated to 4.82, 5.03, and 5.63, respectively. The increase

in this metric is also a sign of fragmentation in the landscape (Fig. 5d—SPLIT; Table 4). ED represents the ratio of the perimeter of each patch to its area. The ED of the watershed in the years 2000, 2010, and 2020 was calculated to be 86.86, 92.06, and 101.42, respectively. This trend is indicative of the increasing degradation and deformation of different patches in the landscape (Fig. 5e—ED; Table 4). The increase in the IJI of the landscape from 38.86 in 2000 to 45.05 in 2010 and then to 50.54 in 2020 is reflective of the increasing blending of patches of land-uses over these years (Fig. 5f—IJI; Table 4).

Water yield ecosystem service

To build and execute a WY model, it was necessary (Hu et al. 2020) to collect and prepare a series of inputs including the maps of precipitation, potential evapotranspiration, root-restricting layer depth, plant available water content, land-uses, vegetation, and watershed boundary (Tables 5 and 6), and also the biophysical table in the CVS format (Table 7).

After preparing these inputs, the model of InVEST 3.7.0 was used to simulate the temporal and spatial changes of WY for the years 2000, 2010, and 2020 based on climate and land-use data (Fig. 6). These simulations showed that the WY of the entire Lavasanat watershed in 2000 has been 2,641,734.816 m³. For this year, the mean WY, potential evapotranspiration, and actual evapotranspiration of each individual pixel were 4.990,

1884.446, and 406.748 mm, respectively. For the year 2010, the WY of the entire watershed was estimated to be 3,318,950.915 m³, and the mean WY, potential evapotranspiration, and actual evapotranspiration of each pixel were calculated to be 6.270, 1806.965, and 370.340 mm, respectively. The WY of the watershed for the year 2020 was 7,737,201.215 m³. For this year, the mean WY, potential evapotranspiration, and actual evapotranspiration of each pixel were calculated to be 14.616, 1535.086, and 530.245 mm, respectively. These model calculations showed that the WY in the Lavasanat watershed is increasing. This increase can be attributed to the observed land-use changes and particularly the rampant expansion of built areas (residential land-uses).

Of the watershed's total WY, 1,677,926.367m³ for the year 2000, 2,287,145.055m³ for the year 2010, and 4,908,786.651m³ for the year 2020 have been related to residential areas. The total area of residential areas in the entire watershed has increased from 4,820,578.505m² in 2000 to 6,885,513.787m² in 2010 and then to 10,407,948.705m² in 2020 (Fig. 7).

Relationship between land-use/cover changes and ecological security

Human activities damage ecosystems by destroying their structures and affecting ecological processes (Salvati and Carlucci 2014). Urbanization is the most important driver

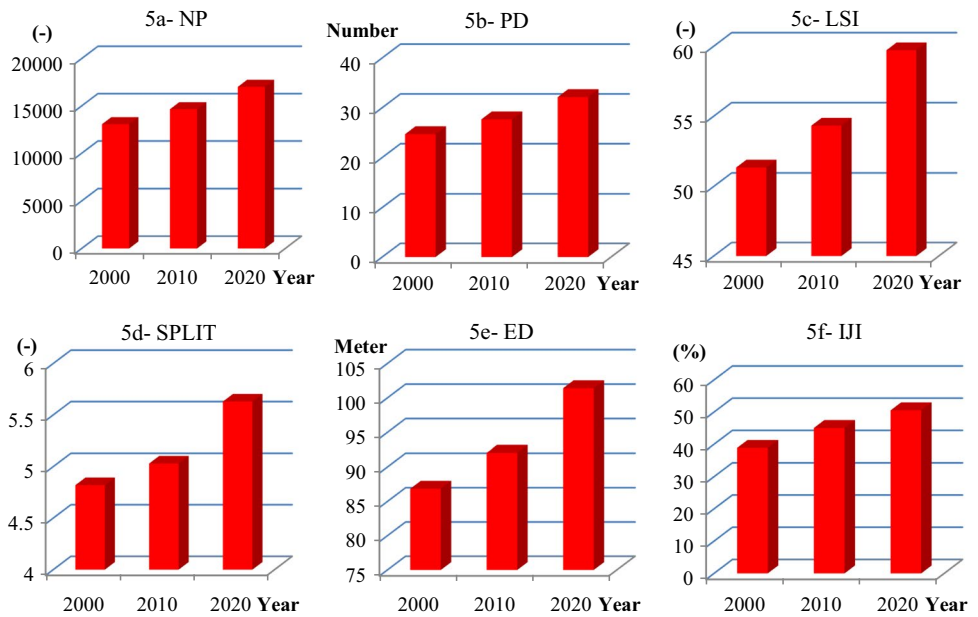Fig. 5 Changing trend of landscape pattern at landscape level

Time	NP	PD	LSI	SPLIT	ED	IJI
2000	13,073	24.69	51.34	4.82	86.86	38.86
2010	14,651	27.67	54.33	5.03	92.06	45.05
2020	17,016	32.14	59.72	5.63	101.42	50.54

Table 4 The overall landscape index changes in the research area

Table 5 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
		Land-use/land-cover[b]	Layer.ras		2010
		Root restricting layer depth[c]	(mm)		2020
		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 6 Data statistics and range of variation for InVEST model inputs

Variables	Value, 2000 (mean, range)	Value, 2010 (mean, range)	Value, 2020 (mean, range)
Precipitation (mm)	411.740 [439.079; 374.788]	376.615 [435.685; 311.061]	544.867 [623.911; 465.793]
Evapotranspiration (mm)	2783.66 [2860.46; 2709.91]	2682.62 [2761.11; 2620.68]	2284.52 [2429.51; 2104.2]
Z	16	14	18
Root restricting layer depth (mm)	0–14,400		

Table 7 Biophysical table used for the baseline InVEST water yield model

Lucode	LULC_desc	LULC_vegatation[a]	Root_depth (mm)	Plant evapotranspiration coefficient K_c[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

of economic development, but undeniably, it is also a major source of environmental problems such as rapid land-use changes (He et al. 2014; Li et al. 2011; Kong et al. 2017; Aljoufie et al. 2013). Ecological and environmental problems caused by rapid land-use changes are in most cases fairly severe. Furthermore, rapid land-use changes may cause fundamental changes in the quality of environmental ecosystems in the short term (Juanita et al. 2019; Wu et al. 2019).

In the absence of advance planning and science-based strategizing, built areas may expand into neighboring environments that play a key role in preserving the ecological security of the entire region. In this study, spatial–temporal analysis of land-use changes in the studied watershed showed that from 2000 to 2020, the watershed's residential areas have

been expanding, its agricultural lands have been shrinking, and there has been not much change in other land-uses (Fig. 3, Table 3). These results are consistent with the findings of Wu et al. (2020), which showed that the expansion of residential and urban areas directly affects ecological security.

Relationship between landscape patterns and ecological security

Identification and monitoring of land-use/cover changes could be an intricate process (Sun and Zhou 2016: 121), especially because such changes may affect ecological processes and functions (Su et al. 2012: 297). One major way to understand and track land-cover and land-use changes is to analyze changes in landscape patterns (Fan and Ding 2016: 156). Landscape patterns can be quantified in terms of landscape metrics (Li and Wu 2004: 224). Using the combination of land-use maps and landscape metrics, one can identify areas with critical changes in ecosystem services at the landscape level. Such knowledge will offer valuable opportunities to improve future land management plans and practices (Tolessa et al. 2017: 49). Landscape structure (composition, configuration, and connectivity) plays an essential role in conserving biodiversity and providing ecosystem services (Zhang and Gao 2016: 42).

Destructive human activities such as land conversion and fragmentation have profoundly affected the landscape of the Lavasanat watershed, leaving a severe adverse environmental impact on this region. This has reduced the area of natural lands in the region and increased their dispersion. The findings show
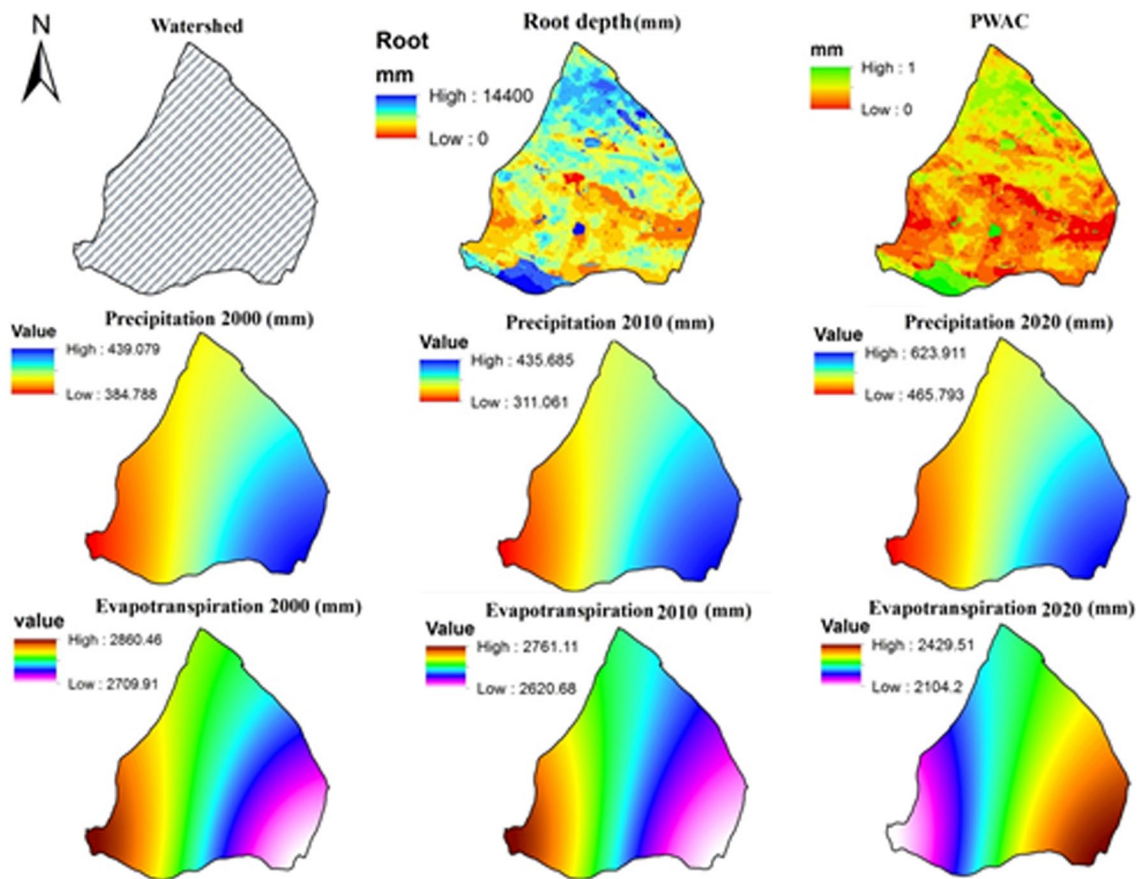
Fig. 6 The used data for InVEST model

that rapid urbanization and population growth in the Lavasanat watershed have altered its ecological structure, resulting in the conversion of agricultural lands into other land-uses. Most of the agricultural lands that have undergone such conversion have turned into residential areas. Further, the results show a decrease in the number and total area and a change in the shape and size of patches of agricultural land in the Lavasanat watershed, causing these patches to turn into small-sized irregularly shaped fragments. The observed changes in the landscape structure indicate that the destruction of the landscape can mostly be attributed to the emergence of new small-sized patches. These results are consistent with the findings of Tong et al. (2017) and Aljoufie et al. (2013) who attributed the changes in land-use and landscape patterns to rapid urbanization and population growth.

The results indicate that poorly controlled real estate development has greatly affected the ecological structure of the Lavasanat watershed. For example, from 2000 to 2020, large agricultural lands, which are of greater ecological value, have been consistently fragmented and replaced with smaller patches with lower ecological value, thus leading to lower ecological security, which is consistent with the results of similar studies (Alberti and Marzluff 2004; Su et al. 2010: 61; Asfaw and Worku 2019: 145). Essentially, the expansion of residential areas

has acted as an interrupting factor, breaking the initial continuity of the watershed's vast natural expanses and undermining its balance and functional dynamism, thereby causing or exacerbating environmental problems such as air pollution, soil erosion, and increased runoff.

Relationship between ecosystem services and ecological security

The concept of ecosystem services and its application in urban environments can offer useful opportunities for gaining a better understanding of the interactions between humans and nature (Tobias 2013). Ecosystem service indicators play a key role in the assessments of ecological security. Therefore, the needs of humans and ecosystems should be analyzed in this framework to determine the deficiencies of these services (Chen et al. 2018). Water supply is a primary component of ecosystem services (Brisbane 2007) that highly depends on natural, economic, and human activities (Sun et al. 2016; Yang et al. 2016; Jie et al. 2015; Liquete et al. 2011). Human activities affect the yield, volume, and availability of water resources by affecting climate, land-use, and water quality (Smith 1997; Chen et al. 2016; Liu et al. 2017).
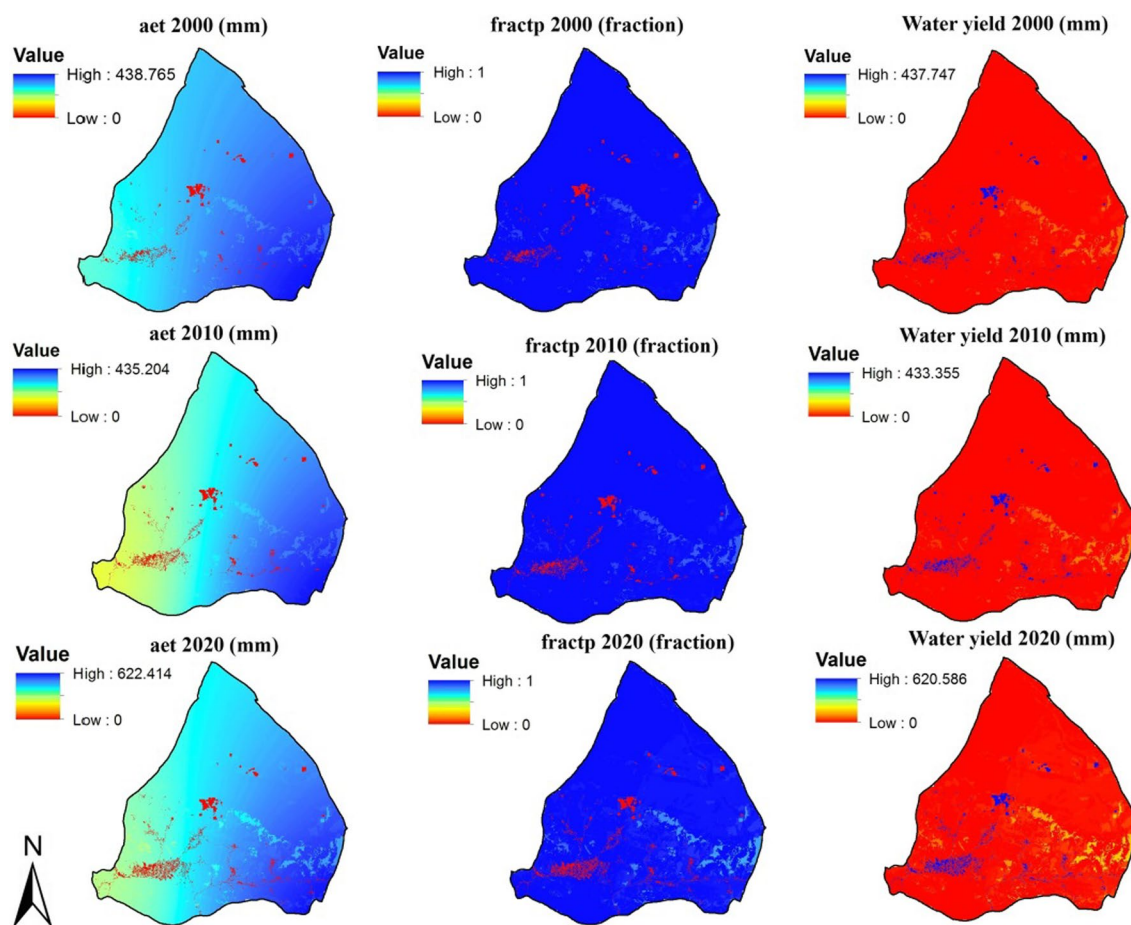
Fig. 7 Spatial distribution of water yield/fractp (estimated actual evapotranspiration fraction per pixel)/aet (estimated actual evapotranspiration per pixel) in the Lavasanat watershed for years 2000, 2010, and 2020

The results of the modeling of WY in the Lavasanat watershed for the last two decades showed an increase in WY because of land-use changes caused by human activities. These results showed that the WY related to residential areas has increased by 1.36-fold from 2000 to 2010 and by 2.14-fold from 2010 to 2020, which sum up to a 2.92-fold increase over these 20 years. Correspondingly, the total area of residential areas in the watershed has increased by 1.42-fold from 2000 to 2010 and by 1.51-fold from 2010 to 2020, which sum up to a 2.15-fold increase for these 20 years. These results are consistent with the findings of several other studies that have demonstrated the great impact of human activities and the expansion of residential areas on the volume and availability of water resources (Smith 1997; Chen et al. 2016; Yang et al. 2016; Sun et al. 2016; Liu et al. 2017).

Analyses show that the total WY of the watershed has experienced a 1.25-fold increase from 2000 to 2010 and a 2.33-fold increase from 2010 to 2020, resulting in a 2.92-fold increase in water yield over the entire period between 2000 and 2020. Our results indicated that climatic data can have a significant impact on WY. For example, an increase in precipitation of the

year 2020 was found to cause a sudden increase in the WY of this year. This result is consistent with the results of many other studies that have shown the great effect of precipitation on the outputs of the WY model (Rahimi et al. 2020; Boithias et al. 2014; Terrado et al. 2014). Finally, it was also observed that the watershed's WY is greatly influenced by climatic factors, among which precipitation is the most effective. Nevertheless, the effect of the type and density of vegetation cover on WY should not be ignored. Thus, considering the importance of securing water supply for the people living in the region and the ongoing problems in this regard, the model can be used to obtain a relative estimate of WY and assess the role of vegetation in changing the WY so as to recharge underground aquifers.

Conclusion

While the environment consists of countless interconnected systems and components, in modern times, LULC changes have emerged as one of the most important determinants of change in ecological systems (Mondal and Southworth 2010: 1716).

In this study, the LULC maps obtained from satellite images (2000, 2010, and 2020) and physical data were used to simulate urban expansion and LULC changes in the Lavasanat watershed. Then, landscape metrics (at the class and landscape level) and ecosystem services (water yield) were used to assess the ecological security of this area.

One of the most important processes commonly observed in urbanizing landscapes is fragmentation, which represents the disturbances caused by human activities in the landscape structure and function (Ahern and Andre 2003: 65–93). Hence, landscape fragmentation also has an impact on the region's ecosystem services and functions (Peng et al. 2016: 1083). The results of this study showed a rapid growth in the region's residential areas, which has caused the landscape to disintegrate and fragment, thereby undermining the region's ESs and consequently ecological security over the past 20 years. For example, the increasing number of patches of built areas in the region and their integration with each other has increased the region's water yield, or in other words, led to a significant positive relationship between LPI and water yield in residential areas, which is consistent with the results of Hu et al. (2020). While the results showed a degree of shrinking and degradation in rangelands and bare lands of Lavasanat watershed, these changes are not as critical as changes in agricultural lands, although this could be because most of these lands are located in areas with high slopes and elevations, which are out of human reach.

The results also showed that given the short distance between urban and rural areas and the presence of several low-density and scattered settlements in the region that face no physical or geographical barriers for expansion, the existing patches of built areas are likely to continue growing and join together. Because of this trend, in the future, the region will have fewer patches, less fragmentation, simpler and more regular geometries, and more cohesiveness and continuity at the landscape level. At the class level, the results show that with the continuation of the current trend, there will be a decrease in the number of all kinds of patches except bare lands. While in the built areas, this will be due to the joining of small patches emerged in previous years, in other classes, this will be mostly due to the conversion of small patches to residential areas.

Moreover, the results of the InVEST scenario-generator model and the water yield model showed that the expansion of built (residential) land-uses in the studied region has led to significantly increased water yield and, consequently, increased runoff. It was also found that the sudden increase in water yield in 2020 can partly be attributed to increased precipitation due to climate change in this year. This demonstrates the great importance of precipitation as an input of the InVEST model, which has also been proven in many other studies (Yang et al. 2019; Hamel and Guswa 2015; Marquès et al. 2013). Also, the maps produced by the model indicate that the expansion of residential areas and the shrinking of agricultural areas and rangelands (because of conversion into residential areas) have disrupted the water balance of the Lavasanat watershed, causing increased runoff in this area. These changes will certainly have significant environmental consequences, such as increased soil erosion, reduced regional groundwater recharge, and easier contaminant displacement.

In conclusion, it should be stated that further expansion of infrastructure and human activities in the Lavasanat region without attention to its capacities will certainly pose many problems for the ecological security of the Lavasanat watershed in the future. Therefore, to avoid these problems, it is essential to formulate management plans in line with the principles of sustainable development, make an assessment of landscape potentials, and make sure that the region's resources are utilized properly so as to prevent unintended change in the region's structure and preserve its spatial cohesion. Also, it is necessary to adopt a new development plan for the Lavasanat watershed with a focus on the protection and preservation of its green areas, because otherwise the continuation of the current trends is expected to lead to further degradation of natural lands and the increased expansion of built land-uses and specifically residential areas.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Ahern J, Andre L (2003) Applying landscape ecological concepts and metrics in sustainable landscape planning. Landsc Urban Plan 59(2):65–93. https://doi.org/10.1016/S0169-2046(02)00005-1

Alberti M, Marzluff J (2004) Ecological resilience in urban ecosystems: linking urban patterns to human and ecological functions. Urban Ecosyst 7(3):241–265. https://doi.org/10.1023/B:UECO.0000044038.90173.c6

Aljoufie M, Zuidgeest M, Brussel M, Maarseveen MV (2013) Spatial–temporal analysis of urban growth and transportation in Jeddah City, Saudi Arabia. Cities 31:57–68. https://doi.org/10.1016/j.cities.2012.04.008

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration—guidelines for computing crop water requirements—FAO irrigation and drainage paper 56. FAO, Rome, p 300

Asfaw M, Worku H (2019) Quantification of the land use/land cover dynamics and the degree of urban growth goodness for sustainable urban land use planning in Addis Ababa and the surrounding Oromia special zone. J Urban Manag 8(1):145–158. https://doi.org/10.1016/j.jum.2018.11.002

Bächler G, Eaton DJ, Eaton JW, Falkenmark M, Ghosh PS, Isaac J, Kliot N, Markakis J, Mayor R, Rogers KS (1995) Environmental crisis: regional conflicts and ways of cooperation. Neotrop Entomol 39(5):681–685

Berkes F, Folke C (1998) Linking social and ecological systems: management practices and social mechanisms for building resilience. Cambridge University Press, Cambridge

Boithias L, Acuña V, Vergoñós L, Ziv G, Marcé R, Sabater S (2014) Assessment of the water supply: demand ratios in a Mediterranean basin under different global change scenarios and mitigation alternatives. Sci Total Environ 470:567–577. https://doi.org/10.1016/j.scitotenv.2013.10.003

Brauman KA, Daily GC, Duarte TKE, Mooney HA (2007) The nature and value of ecosystem services: an overview highlighting hydrologic services. Annu Rev Environ Resour 32:67–98. https://doi.org/10.1146/annurev.energy.32.031306.102758

Brisbane Declaration (2007) The Brisbane declaration: environmental flows are essential for freshwater ecosystem health and human well-being. In: 10th international river symposium, Brisbane, pp 3–6

Budyko MI (1974) Climate and life. Academic Press, New York

Canqiang Z, Wenhua L, Biao Z, Moucheng L (2012) Water yield of Xitiaoxi River Basin based on INVEST modeling. J Resour Ecol 3(1):50–54. https://doi.org/10.5814/j.issn.1674-764x.2012.01.008

Chen A, Yao L, Sun R, Chen L (2014) How many metrics are required to identify the effects of the landscape pattern on land surface temperature? Ecol Ind 45:424–433. https://doi.org/10.1016/j.ecolind.2014.05.002

Chen L, Sun R, Yang L (2018) Regional eco-security: concept, principles and pattern design, challenges towards ecological sustainability in China. Springer International Publishing, Berlin. https://doi.org/10.1007/978-3-030-03484-9_2

Chen M, Qin X, Zeng G, Li J (2016) Impacts of human activity modes and climate on heavy metal "spread" in groundwater are biased. Chemosphere 152:439–445. https://doi.org/10.1016/j.chemosphere.2016.03.046

Chen N, Qin F, Zhai Y, Zhang R, Cao F (2020) Evaluation of coordinated development of forestry management efficiency and forest ecological security: a spatiotemporal empirical study based on China's provinces. J Clean Prod 260:121042. https://doi.org/10.1016/j.jclepro.2020.121042

Cumming GS, Allen CR (2017) Protected areas as social-ecological systems: perspectives from resilience and social-ecological systems theory. Ecol Appl 27(6):1709–1717. https://doi.org/10.1002/eap.1584

De Groot RS, Alkemade R, Braat L, Hein L, Willemen L (2010) Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecol Complex 7(3):260–272. https://doi.org/10.1016/j.ecocom.2009.10.006

Devuyst D, Hens L, De Lannoy W (2001) How green is the city? Sustainability assessment and the management of urban environments. Columbia University Press, New York

Donohue RJ, Roderick ML, McVicar TR (2012) Roots, storms and soil pores: incorporating key ecohydrological processes into Budyko's hydrological model. J Hydrol 436:35–50. https://doi.org/10.1016/j.jhydrol.2012.02.033

Du Y, Teillet PM, Cihlar J (2002) Radiometric normalization of multitemporal high-resolution satellite images with quality control for land cover change detection. Remote Sens Environ 82(1):123–134. https://doi.org/10.1016/S0034-4257(02)00029-9

Eckersley R (2005) Ecological security dilemmas. N Environ Agendas II

Ehrlich PR (2002) Human natures, nature conservation, and environmental ethics. Bioscience 52:31–43. https://doi.org/10.1641/0006-3568(2002)052[0031:HNNCAE]2.0.CO;2

Fan Q, Ding S (2016) Landscape pattern changes at a county scale: a case study in Fengqiu, Henan Province, China from 1990 to 2013. Catena J 137:152–160. https://doi.org/10.1016/j.catena.2015.09.012

Feist BE, Buhle ER, Baldwin DH, Spromberg JA, Damm SE, Davis JW, Scholz NL (2017) Roads to ruin: conservation threats to a sentinel species across an urban gradient. Ecol Appl 27:2382–2396. https://doi.org/10.1002/eap.1615

Fu BP (1981) On the calculation of the evaporation from land surface. Atmos Sci 5:23–31 ((in Chinese))

Gao Y, Wu Zh, Lou Q, Huang H, Cheng J, Chen Zh (2012) Landscape ecological security assessment based on projection pursuit in Pearl River Delta. Environ Monit Assess 184:2307–2319. https://doi.org/10.1007/s10661-011-2119-2

Grimm NB, Faeth SH, Golubiewski NE, Redman CL, Wu J, Bai X, Briggs JM, Grimm NB, Faeth SH, Golubiewski NE, Redman CL, Wu J, Bal X, Briggs JM (2015) Global change and the ecology of cities. Science 319(5864):756–760. https://doi.org/10.1126/science.1150195

Haeuber R, Ringold P (1998) Ecology, the social sciences, and environmental policy. Ecol Appl 8(2):330–331

Hamel P, Guswa AJ (2015) Uncertainty analysis of a spatially explicit annual water-balance model: case study of the Cape Fear basin, North Carolina. Hydrol Earth Syst Sci 19(2):839–853. https://doi.org/10.5194/hess-19-839-2015

Hao H, Bin Ch, Zhiyuan M, Zhenghua L, Senlin Zh, weiwei Y, Jianji L, Wenjia H, Jianguo D, Guangcheng Ch, (2017) Assessing the ecological security of the estuary in view of the ecological services—a case study of the Xiamen Estuary. Ocean Coast Manag 137:12–23. https://doi.org/10.1016/j.ocecoaman.2016.12.003

He C, Liu Z, Tian J, Ma Q (2014) Urban expansion dynamics and natural habitat loss in China: a multiscale landscape perspective. Glob Change Biol 20:2886–2902. https://doi.org/10.1111/gcb.12553

Hu W, Li G, Gao Zh, Jia G, Wang Zh, Li Y (2020) Assessment of the impact of the poplar ecological retreat project on water conservation in the Dongting Lake wetland region using the InVEST model. Sci Total Environ 733:139423. https://doi.org/10.1016/j.scitotenv.2020.139423

Jie X, Yu X, Na L, Hao W (2015) Spatial and temporal patterns of supply and demand balance of water supply services in the Dongjiang Lake Basin and its beneficiary areas. J Resour Ecol 6(6):386–396. https://doi.org/10.5814/j.issn.1674-764x.2015.06.006

Juanita A-D, Ignacio P, Jorgelina GA, Cecilia AS, Carlos M, Francisco N (2019) Assessing the effects of past and future land cover changes in ecosystem services, disservices and biodiversity: a case study in Barranquilla Metropolitan Area (BMA), Colombia. Ecosyst Serv 37:100915. https://doi.org/10.1016/j.ecoser.2019.100915

Kattel GR, Elkadi H, Meikle H (2013) Developing a complementary framework for urban ecology. Urban for Urban Green 12(4):498–508. https://doi.org/10.1016/j.ufug.2013.07.005

Kim J (2019) Subdivision design and landscape structure: case study of The Woodlands, Texas, US. Urban for Urban Green 38:232–241. https://doi.org/10.1016/j.ufug.2019.01.006

Kong F, Ban Y, Yin H, James P, Dronova I (2017) Modeling storm water management at the city district level in response to changes in land use and low impact development. Environ Model Softw 95:132–142. https://doi.org/10.1016/j.envsoft.2017.06.021

Kullenberg G (2002) Regional co-development and security: a comprehensive approach. Ocean Coast Manag 45(11–12):761–776. https://doi.org/10.1016/S0964-5691(02)00105-9

Lang Y, Song W, Deng X (2017) Projected land use changes impacts on water yields in the Karst mountain areas of China. Phys Chem Earth Parts A/b/c. https://doi.org/10.1016/j.pce.2017.11.001

Li H, Wu J (2004) Use and misuse of landscape indices. Landsc Ecol 19:389–399

Li J, Song C, Cao L, Zhu F, Meng X, Wu J (2011) Impacts of landscape structure on surface urban heat islands: a case study of Shanghai, China. Remote Sens Environ 115(12):3249–3263. https://doi.org/10.1016/j.rse.2011.07.008

Li JX, Chen YN, Xu ChCh, Li Zh (2019a) Evaluation and analysis of ecological security in arid areas of Central Asia based on the emergy ecological footprint (EEF) model. J Clean Prod 235:664–677. https://doi.org/10.1016/j.jclepro.2019.07.005

Li RQ, Dong M, Cui JY, Zhang LL, Cui QG, He WM (2007) Quantification of the impact of land-use changes on ecosystem services: a case study in Pingbian County, China. Environ Monit Assess 128(1–3):503–510

Li S, Xiao W, Zhao Y, Lv X (2020) Incorporating ecological risk index in the multi-process MCRE model to optimize the ecological security pattern in a semi-arid area with intensive coal mining: a case study in

northern China. J Clean Prod 247:119143. https://doi.org/10.1016/j.jclepro.2019.119143

Li Zh, Yuan M, Hu M, Wang Y, Xia B (2019b) Evaluation of ecological security and influencing factors analysis based on robustness analysis and the BP-DEMALTE model: a case study of the Pearl River Delta urban agglomeration. Ecol Ind 101:595–602. https://doi.org/10.1016/j.ecolind.2019.01.067

Liang X, Lettenmaier DP, Wood EF, Burges SJ (1994) A simple hydrologically based model of land surface water and energy fluxes for general circulation models. J Geophys Res Atmos 99(14):14415–14428. https://doi.org/10.1029/94JD00483

Liquete C, Maes J, La Notte A, Bidoglio G (2011) Securing water as a resource for society: an ecosystem services perspective. Ecohydrol Hydrobiol 11(3–4):247–259. https://doi.org/10.2478/v10104-011-0044-1

Liu D, Chang Q (2015) Ecological security research progress in China. Acta Ecol Sin 35(5):111–121. https://doi.org/10.1016/j.chnaes.2015.07.001

Liu P, Jia Sh, Han R, Zhang H (2018) Landscape pattern and ecological security assessment and prediction using remote sensing approach. J Sens 14:1058513. https://doi.org/10.1155/2018/1058513

Liu Y, Song W, Mu F (2017) Changes in ecosystem services associated with planting structures of cropland: a case study in Minle County in China. Phys Chem Earth Parts A/b/c 102:10–20. https://doi.org/10.1016/j.pce.2016.09.003

Lu Sh, Tang X, Guan X, Qin F, Liu X, Zhang D (2020) The assessment of forest ecological security and its determining indicators: a case study of the Yangtze River Economic Belt in China. J Environ Manag 258:110048. https://doi.org/10.1016/j.jenvman.2019.110048

Ma KM, Fu BJ, Li XY (2004) The regional pattern for ecological security (RPES): the concept and theoretical basis. Acta Ecol Sin 24(4):761–768

Ma L, Bo J, Li X, Fang F, Cheng W (2019) Identifying key landscape pattern indices influencing the ecological security of inland river basin: the middle and lower reaches of Shule River Basin as an example. Sci Total Environ 674:424–438. https://doi.org/10.1016/j.scitotenv.2019.04.107

MacMillan RA, Moon DE, Coupe RA (2007) Automated predictive ecological mapping in a Forest Region of B.C., Canada, 2001–2005. Geoderma 140(4):353–373. https://doi.org/10.1016/j.geoderma.2007.04.027

Marquès M, Bangash RF, Kumar V, Schuhmacher M, Sharp R (2013) The impact of climate change on water provision under a low flow regime: a case study of the ecosystems services in the Francoli river basin. J Hazard Mater 263(1):224–232. https://doi.org/10.1016/j.jhazmat.2013.07.049

Matthew R, Halle M, Switzer J (2002) Conserving the peace: resources, livelihoods and security. International Institute for Sustainable Development, Winnipeg

Mcdonald RI, Kareiva P, Forman RTT (2008) The implications of current and future urbanization for global protected areas and biodiversity conservation. Biol Conserv 141(6):1695–1703. https://doi.org/10.1016/j.biocon.2008.04.025

McGarigal K, Cushman SA, Ene E (2012) FRAGSTATS v4: spatial pattern analysis program for categorical and continuous maps. University of Massachusetts, Amherst

Mondal P, Southworth J (2010) Evaluation of conservation interventions using a cellular automata-Markov model. For Ecol Manag 260(10):1716–1725. https://doi.org/10.1016/j.foreco.2010.08.017

Pan Zh, Wang G, Hu Y, Cao B (2019) Characterizing urban redevelopment process by quantifying thermal dynamic and landscape analysis. Habitat Int 86:61–70. https://doi.org/10.1016/j.habitatint.2019.03.004

Pasgaard M, Van Hecken G, Ehammer A, Strange N (2017) Unfolding scientific expertise and security in the changing governance of

ecosystem services. Geoforum 84:354–367. https://doi.org/10.1016/j.geoforum.2017.02.001

Peng J, Liu Y, Liu Z, Yang Y (2017) Mapping spatial non-stationarity of human-natural factors associated with agricultural landscape multi-functionality in Beijing-Tianjin-Hebei region, China. Agr Ecosyst Environ 246:221–233. https://doi.org/10.1016/j.agee.2017.06.007

Peng J, Pan YJ, Liu YX, Zhao HJ, Wang YL (2018a) Linking ecological degradation risk to identify ecological security patterns in a rapidly urbanizing landscape. Habitat Int 71:110–124. https://doi.org/10.1016/j.habitatint.2017.11.010

Peng J, Shen H, Wu W, Liu Y, Wang Y (2016) Net primary productivity (NPP) dynamics and associated urbanization driving forces in metropolitan areas: a case study in Beijing city, China. Landsc Ecol 31(5):1077–1092. https://doi.org/10.1007/s10980-015-0319-9

Peng J, Yang Y, Liu YX, Hu YN, Du YY, Meersmans J, Qiu SJ (2018b) Linking ecosystem services and circuit theory to identify ecological security patterns. Sci Total Environ 644:781–790. https://doi.org/10.1016/j.scitotenv.2018.06.292

Peng J, Zhao SQ, Dong JQ, Liu YX, Meersmans J, Li HL, Wu JS (2019) Applying ant colony algorithm to identify ecological security patterns in megacities. Environ Model Softw 117:214–222. https://doi.org/10.1016/j.envsoft.2019.03.017

Qin K, Liu J, Yan L, Huang H (2019) Integrating ecosystem services flows into water security simulations in water scarce areas: present and future. Sci Total Environ 670:1037–1048. https://doi.org/10.1016/j.scitotenv.2019.03.263

Rahimi L, Malekmohammadi B, Yavari AR (2020) Assessing and modeling the impacts of wetland land cover changes on water provision and habitat quality ecosystem services. Nat Resour Res 29:3701–3718. https://doi.org/10.1007/s11053-020-09667-7

Rahmani Fazli A, Monshizadeh R, Rahmani B, Alipourian J (2017) Good governance based rural management and its role in sustainable rural development (case study: a comparison between central district of Kuhdasht and Lavasanat District of Shemiranat). J Res Rural Plan 6(17):133–152

Redhead JW, Stratford C, Sharps K, Jones L, Ziv G, Clarke D, Oliver TH, Bullock JM (2016) Empirical validation of the InVEST water yield ecosystem service model at a national scale. Sci Total Environ 569:1418–1426. https://doi.org/10.1016/j.scitotenv.2016.06.227

Salvati L, Carlucci M (2014) Zero net land degradation in Italy: the role of socioeconomic and agro-forest factors. J Environ Manag 145:299–306. https://doi.org/10.1016/j.jenvman.2014.07.006

Seto KC, Guneralp B, Hutyra LR (2012) Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proc Natl Acad Sci 109(40):16083–16088. https://doi.org/10.1073/pnas.1211658109

Sharp R, Tallis HT, Ricketts T, Guerry AD, Wood, SA, Chaplin-Kramer R et al (2019) InVEST 3.7.0 users guide. The natural capital project. Stanford University, University of Minnesota, The Nature Conservancy and World Wildlife Fund

Sharp R, Tallis HT, Ricketts T, Guerry AD, Wood SA, Chaplin-Kramer R, Nelson E, Ennaanay D, Wolny S, Olwero N, Vigerstol K (2014) InVEST user's guide. The natural capital project Stanford 161p

Smith EJ (1997) The balance between public water supply and environmental needs. Water Environ J 11(1):8–13. https://doi.org/10.1111/j.1747-6593.1997.tb00082.x

Solovjova NV (1999) Synthesis of ecosystemic and ecoscreening modelling insolving problems of ecological safety. Ecol Model 124(1):1–10. https://doi.org/10.1016/S0304-3800(99)00122-2

Su Sh, Xiao R, Jiang Z, Zhang Y (2012) Characterizing landscape pattern and ecosystem service value changes for urbanization impacts at an eco-regional scale. Appl Geogr 34:295–305. https://doi.org/10.1016/j.apgeog.2011.12.001

Su W, Gu C, Yang G, Chen S, Zhen F (2010) Measuring the impact of urban sprawl on natural landscape pattern of the Western Taihu Lake

watershed, China. Landsc Urban Plan 95(1–2):61–67. https://doi.org/10.1016/j.landurbplan.2009.12.003

Su YX, Zhang HO, Chen XZ, Huang GQ, Ye YY, Wu QT, Huang NS, Kuang YQ (2013) The ecological security patterns and construction land expansion simulation in Gaoming. Acta Ecol Sin 33(5):1524–1534. https://doi.org/10.5846/stxb201205160733

Sun S, Sun G, Cohen E, McNulty SG, Caldwell PV, Duan K, Zhang Y (2016) Projecting water yield and ecosystem productivity across the United States by linking an ecohydrological model to WRF dynamically downscaled climate data. Hydrol Earth Syst Sci 20(2):935–952. https://doi.org/10.5194/hess-20-935-2016

Sun B, Zhou Q (2016) Expressing the spatio-temporal pattern of farmland change in arid lands using landscape metrics. J Arid Environ 124:118–127. https://doi.org/10.1016/j.jaridenv.2015.08.007

Talari A (2016) Morphometric analysis Lavasanat basin and affecting drainge network changes, University of Tehran, Faculty of Geography, Thesis submitted to the graduate studies office In partial fulfillment requirements for the degree of MSC, Under Supervision pf: Dr. Ebtahim Moghimi and Mojtaba Yamani

Tao JIN, Xiaoyu Q, Liyan H (2016) Changes in grain production and the optimal spatial allocation of water resources in China. J Resour Ecol 7(1):28–35. https://doi.org/10.5814/j.issn.1674-764X.2016.01.004

Terrado M, Acuña V, Ennaanay D, Tallis H, Sabater S (2014) Impact of climate extremes on hydrological ecosystem services in a heavily humanized Mediterranean basin. Ecol Ind 37:199–209. https://doi.org/10.1016/j.ecolind.2013.01.016

Tobias S (2013) Preserving ecosystem services in urban regions: challenges for planning and best practice examples from Switzerland. Integr Environ Assess Manag 9(2):243–251. https://doi.org/10.1002/ieam.1392

Tolessa T, Senbeta F, Kidane M (2017) The impact of land use/land cover change on ecosystem services in the central highlands of Ethiopia. Ecosyst Serv 23:47–54. https://doi.org/10.1016/j.ecoser.2016.11.010

Tong I, Hu S, Frazier A, Liu Y (2017) Multi-order urban development model and sprawl patterns: an analysis in China, 2000–2010. Landsc Urban Plan 167(1):386–398. https://doi.org/10.1016/j.landurbplan.2017.07.001

Wang H, Qin F, Zhang X (2019) A spatial exploring model for urban land ecological security based on a modified artificial bee colony algorithm. Ecol Inform 50:51–61. https://doi.org/10.1016/j.ecoinf.2018.12.009

Wu J, Zhang L, Peng J, Feng Z, Liu H, He S (2013) The integrated recognition of the source area of the urban ecological security pattern in Shenzhen. Acta Ecol Sin 33(13):4125–4133. https://doi.org/10.5846/stxb201208081123

Wu X, Liu Sh, Sun Y, An Y, Dong Sh, Liu G (2019) Ecological security evaluation based on entropy matter-element model: a case study of Kunming city, southwest China. Ecol Ind 102:469–478. https://doi.org/10.1016/j.ecolind.2019.02.057

Wu Y, Zhang T, Zhang H, Pan T, Ni X, Grydehøj A, Zhang J (2020) Factors influencing the ecological security of island cities: a neighbourhood scale study of Zhoushan Island, China. Sustain Cities Soc 55:102029. https://doi.org/10.1016/j.scs.2020.102029

Xu X, Liu W, Scanlon BR, Zhang L, Pan M (2013) Local and global factors controlling water-energy balances within the Budyko framework. Geophys Res Lett 40(23):6123–6129. https://doi.org/10.1002/2013GL058324,2013

Yang D, Liu W, Tang L, Chen L, Li X, Xu X (2019) Estimation of water provision service for monsoon catchments of South China: applicability of the InVEST model. Landsc Urban Plan 182:133–143. https://doi.org/10.1016/j.landurbplan.2018.10.011

Yang Q, Liu G, Hao Y, Coscieme L, Zhang J, Jiang N, Casazza M, Giannetti BF (2018) Quantitative analysis of the dynamic changes of ecological security in the provinces of China through emergy-ecological footprint hybrid indicators. J Clean Prod 184:678–695. https://doi.org/10.1016/j.jclepro.2018.02.271

Yang X, Zhou Z, Li J, Fu X, Mu X, Li T (2016) Trade-offs between carbon sequestration, soil retention and water yield in the Guanzhong-Tianshui Economic Region of China. J Geogr Sci 26(10):1449–1462. https://doi.org/10.1007/s11442-016-1337-5

Yang Y, Cai Z (2020) Ecological security assessment of the Guanzhong Plain urban agglomeration based on an adapted ecological footprint model. J Clean Prod 260:120973. https://doi.org/10.1016/j.jclepro.2020.120973

Yu K (1995) Security patterns in landscape planning: with a case in South China. Dissertation, Harvard University

Yu K, Li D, Li N (2006) The evolution of greenways in China. Landsc Urban Plan 76(1–4):223–239. https://doi.org/10.1016/j.landurbplan.2004.09.034

Yu KJ (1996) Security patterns and surface model in landscape ecological planning. Landsc Urban Plan 36(1):1–17. https://doi.org/10.1016/S0169-2046(96)00331-3

Yu M, Huang Y, Cheng X, Tian J (2019) An ArcMap plug-in for calculating landscape metrics of vector data. Ecol Inform 50:207–219. https://doi.org/10.1016/j.ecoinf.2019.02.004

Zhang L, Hickel K, Dawes WR, Chiew FH, Western AW, Briggs PR (2004) A rational function approach for estimating mean annual evapotranspiration. Water Resour Res 40:W02502. https://doi.org/10.1029/2003WR002710

Zhang LQ, Peng J, Liu YX, Wu JS (2017) Coupling ecosystem services supply and human ecological demand to identify landscape ecological security pattern: a case study in Beijing-Tianjin-Hebei region, China. Urban Ecosyst 20(3):701–714. https://doi.org/10.1007/s11252-016-0629-y

Zhang R, Pu L, Li J, Zhang J (2016) Landscape ecological security response to land use change in the tidal flat reclamation zone, China. Environ Monit Assess 188(1):1. https://doi.org/10.1007/s10661-015-4999-z

Zhang YJ, Yu BY, Ashraf MA (2015) Ecological security pattern for the landscape of mesoscale and microscale land: a case study of the Harbin city center. J Environ Eng Landsc Manag 23(3):192–201. https://doi.org/10.3846/16486897.2015.1036872

Zhang Z, Gao J (2016) Linking landscape structures and ecosystem service value using multivariate regression analysis: a case study of the Chaohu Lake Basin, China. Environ Earth Sci 75:38–51. https://doi.org/10.1007/s12665-015-4862-0

Zhao YZ, Zou XY, Cheng H, Jia HK, Wu YQ, Wang GY, Zhang CL, Gao SY (2006) Assessing the ecological security of the Tibetan plateau: methodology and a case study for Lhaze County. J Environ Manag 80(2):120–131. https://doi.org/10.1016/j.jenvman.2005.08.019

Zhaoxue L, Linyu X (2010) Evaluation indicators for urban ecological security based on ecological network analysis. Int Soc Environ Inf Sci 2010 Annu Conf Proc Environ Sci 2:1393–1399. https://doi.org/10.1016/j.proenv.2010.10.151