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Article

Spatiotemporal analysis of urbanization-driven land use changes in Tehran Province using novel technologies

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Abstract: Land use changes have been demonstrated to exert a significant influence on urban planning and sustainable development, particularly in regions undergoing rapid urbanization. Tehran Province, as the political and economic capital of Iran, has undergone substantial growth in recent decades. The present study employs sophisticated Geographic Information System (GIS) instruments and the Google Earth Engine (GEE) platform to comprehensively track and analyze land use change over the past two decades. A comprehensive analysis of Landsat images of the Tehran metropolitan area from 2003 to 2023 has yielded significant insights into the patterns of land use change. The methodology encompasses the utilization of GIS, GEE, and TerrSet techniques for image classification, accuracy assessment, and change detection. The Kappa coefficients for the maps obtained for 2016 and 2023 were 0.82 and 0.87 for four classes: built-up, vegetation cover, barren land, and water bodies. The findings suggest that, over the past two decades, Tehran Province has undergone a substantial decline in ecological and vegetative areas, amounting to 2.4% (458.3 km^2). Concurrently, the urban area and the barren lands have expanded by 287.5 and 125.5 km^2, respectively. The increase in water bodies during this period is likely attributable to the reduction of vegetation cover and dam construction in the region. The present study demonstrates that remote sensing and GIS are excellent tools for monitoring environmental and sustainable urban development in areas experiencing rapid urbanization and land use changes.

Keywords: remote sensing; land use change; Google Earth Engine; TerrSet; Tehran Province

1. Introduction

Urbanization, a phenomenon that has come to define the 21st century, is rapidly transforming natural landscapes and ecological systems, particularly in developing countries [1,2]. According to United Nations projections, the global trajectory of urbanization is accelerating [3], with the global urban population surpassing 4.7 billion in 2023 and expected to increase by an additional 2.8 billion by 2050 [4]. This intensified urbanization trend has profound implications for land use patterns, the consumption of natural resources, and environmental sustainability. In many cases, this has resulted in unplanned development and environmental degradation [5–7].

In developing countries, urban sprawl is frequently regarded as a consequence of regional transformations associated with cultural, social, and economic aspects of national and regional policies. In metropolitan areas, social and economic factors exert a significant influence on urban development. In contemporary and postmodern times, the formation of peripheral societies has led to the emergence of diverse patterns in these areas [1]. This process has the potential to result in geographically uneven growth, such as urban sprawl, which first emerged in U.S. cities in the aftermath of World War II. Since the 1960s, the phenomenon of urban sprawl has been a recurrent theme in urban discourse, and it is now widely recognized as a global phenomenon impacting both developing and developed countries [8].

In recent decades, Iran has experienced significant urbanization, which has resulted in the encroachment of housing and industrial activities into natural areas and sparsely populated agricultural lands [9]. Despite being regarded as one of the most urbanized developing nations [10], Iran continues to experience a notable dearth of contemporary spatial data concerning urban expansion and urbanization patterns nationwide [11]. The generation of accurate spatial maps and data concerning urban areas has been demonstrated to enhance understanding of the influence of population growth on urbanization trends and land use dynamics [9].

It is unfortunate that conventional methodologies employed in the production of land use change maps, particularly in developing countries such as Iran, frequently entail a considerable investment of time and financial resources. Consequently, in recent years, researchers have increasingly turned to geographic information systems (GIS) and remote sensing (RS) technologies for monitoring land use change. RS data and GIS-based methods have been extensively employed for land use mapping, land use change analysis, and urban development assessments due to their cost-effectiveness and high efficiency [12–15].

As Mukherjee et al. [16] demonstrate, remote sensing provides precise spatial data, while GIS offers robust tools for the effective management of environmental and ecosystem data. The assessment of changes in land use is predominantly reliant on multispectral RS data. The utilization of multi-temporal satellite imagery has engendered substantial scientific opportunities, particularly in the domain of analyzing land use trends. Satellite images, particularly those captured by Landsat sensors, play a critical role in the detection and analysis of land use changes [17,18].

GEE is a prominent cloud-based platform for the storage and processing of large-scale spatial datasets. It provides researchers with access to powerful computational resources and facilitates the sharing of analytical algorithms. GEE has been developed to streamline land use studies by enabling efficient management of large-scale geospatial data. With access to extensive satellite imagery and geospatial datasets, researchers are equipped to analyze changes in land use and land cover [19]. Furthermore, GEE supports advanced machine learning techniques, which significantly enhance the accuracy of land use classification and change detection, thereby contributing to the advancement of research in this field [20].

Land use has been identified as a fundamental indicator of the multiple interconnections between human societies and natural environments [21]. In recent decades, an increase in human activity has led to an acceleration in land use change, which has resulted in a multitude of problems for ecosystems, climate, biodiversity, and food security [22]. The prevailing focus in contemporary research is on urbanization, a process that exerts a significant influence on the global landscape, particularly in developing countries such as Iran. The transition from natural cover to artificial surfaces has been demonstrated to engender adverse social and ecological consequences, giving rise to concerns regarding ecology, human settlements, and public health, despite the presence of certain benefits [23]. The capacity to discern land use enables the identification of potential environmental occurrences associated with rapid urbanization, ecological space destruction, and agricultural expansion. These alterations are indicative of human activity and have the potential to result in biodiversity loss and land degradation [24]. Furthermore, the assessment and monitoring of land use change is imperative for the formulation of integrated management strategies for water and land resources, with the objective of promoting urban sustainability and ecological balance.

Land use transformations driven by rapid urbanization have emerged as a critical area of research. Recent studies indicate that the field of land use changes research has been growing at an annual rate of 24.37% [25]. Globally, approximately 62% of land areas have undergone substantial transformations, predominantly shifting from natural cover to agricultural lands and urban settlements. The magnitude of these changes has been shown to be strongly correlated with regional characteristics and urbanization rates [26].

Consequently, the study of land use changes and urban expansion has undergone significant methodological evolution over the past two decades. The initial scientific endeavors in this domain were predicated on the utilization of coarse-scale satellite imagery, which was employed to generate broad-scale maps. Schneider et al. [27] were the first to produce global maps of urban expansion using MODIS imagery, and they identified distinct urbanization patterns in developed versus developing countries. Their fundamental research revealed that urbanization in developing nations tends to follow a dispersed and imbalanced growth pattern.

Subsequent studies have shifted towards long-term temporal analyses, driven by advancements in remote sensing technologies. Li et al. [28] conducted a comprehensive study utilizing Landsat time-series data (1985–2015) and demonstrated that in numerous regions across Asia, the conversion of agricultural lands to urban areas has been the primary driver of land use changes. This period also marked the rise of cloud-based processing platforms, which were elaborated by Tamiminia et al. [29]. These scholars highlighted the transformative capabilities of the GEE platform in satellite image processing.

In recent years, there has been a paradigm shift in the field of remote sensing, largely due to the integration of this technology with intelligent predictive models. Koko et al. [30] successfully predicted land use changes in Zhejiang Province, China, by combining cellular automata with the advanced PLUS algorithm. The findings of the study indicated that the implementation of conservation policies could result in a reduction of up to 40% in urban expansion that is deemed unnecessary. Concurrently, Wu et al. [31] utilized a spatial Durbin model to substantiate the pivotal function of economic drivers in propelling urban expansion in China’s coastal regions.

Recent advancements in the field of land use studies have been observed in 2024 and 2025, with a notable shift towards a more comprehensive examination of the ecological and social ramifications of land use alterations. In a quantitative analysis, Khan et al. [3] established a direct relationship between an increase in urban surface temperature of 11.35 °C and a reduction in vegetative cover of 24.55% in Aligarh, India. Wei et al. [32] demonstrated that the adoption of “sustainable development” policies could reduce ecological risks by up to 30% in comparison with purely economic scenarios. This was achieved through the development of four urban development scenarios in the Chengdu Plain.

Zhu and Ling [33] reported a decline in the amount of urban open space in Shanghai, from 91.83% in 1980 to 69.63% in 2020. The study identified socioeconomic factors as key drivers of this change. In the Danjiangkou watershed, Wang et al. [34] evaluated ecosystem service values and revealed a complex relationship between land use changes and ecological value. Zhang et al. [4] utilized GEE and predictive models in the Multan and Sargodha regions of Pakistan to analyze the increase in built-up areas. They proposed an integrated approach for assessing spatiotemporal patterns. Mansingh et al. [35] documented a substantial decrease in forest cover, from 854.79 to 386.4 km^2, in the Jharsuguda region of India over the period 1993 to 2023. This decline underscores the pressing need for effective sustainable land use planning strategies.

In Iran, a significant number of studies have concentrated on the subject of land use changes and urban expansion. A notable example is the study conducted by Parsa and Salehi [36], who analyzed changes in land use in the city of Naqadeh over a 27-year period (1987–2014) using satellite imagery from the Landsat program. Employing the CA-Markov model, they projected future changes up to 2041 and found that, if current trends persist, barren lands would shrink while urban areas expand. In 2017, Taravat et al. [37] utilized artificial neural networks to analyze urbanization dynamics in Tehran over a 40-year period (1975–2015). The researchers' findings revealed that rapid population growth and unplanned urban development have resulted in environmental degradation and imbalanced growth across the city.

Rousta et al. [38] conducted a comprehensive study in which they investigated land use changes and their effects on urban heat islands in Tehran over a 30-year period (1988–2018). The findings indicated a 48.27% increase in impervious surfaces and a 7.10% decline in vegetative cover. Furthermore, an increase in surface temperatures of 2 °C–3 °C was observed in central areas and 5 °C–7 °C in peripheral zones, thus demonstrating the correlation between land use changes and urban heat intensification. Another pertinent study by Zenouzi et al. [39] analyzed vegetation cover changes in Tehran between 1990 and 2020 using the NDVI index and Geographically Weighted Regression (GWR) method. The study documented a precipitous decline in vegetative cover, from 38,936.80 hectares to 4663.23 hectares, attributing this reduction primarily to urban expansion and increasing population density.

In the context of Iranian metropolises, irregular land use change and destruction represent significant challenges, resulting in alterations to the structure and function of ecosystems, thereby engendering increased instability within these regions and communities [1,40]. The urban expansion of Tehran has been a subject of considerable interest in recent decades, with the city undergoing significant physical development. This expansion has had a considerable impact on the city's ecological spaces, resulting in the destruction or conversion of many of these spaces. This region has undergone numerous changes for various reasons and faces multiple challenges, with habitats severely threatened. One of the primary factors driving land use change in this region is the intense urbanization and associated activities, such as the creation of industrial space, the construction of buildings, and the development of infrastructure [41].

Tehran, a city undergoing rapid population growth and high urbanization, has been identified as the fastest-growing city in the country. Consequently, the city is confronted with numerous environmental challenges, including water and air pollution, natural resource depletion, and ecosystem degradation [42]. Consequently, the study of land use change in Tehran can facilitate comprehension of urbanization trends and their environmental ramifications, in addition to providing recommendations for sustainable urban growth.

Despite Tehran's prominent status as the political, economic, and cultural capital of Iran and its decisive role in shaping national urbanization trends, there remains a paucity of comprehensive, data-driven, and long-term understanding of land use change patterns in this megacity. The majority of studies conducted in Iran, particularly those focusing on Tehran, have been either limited to short temporal intervals or constrained by local and regional spatial scales. Furthermore, these models frequently lack an integrated analysis encompassing spatial, temporal, ecological, and social dimensions. Furthermore, the utilization of advanced technologies for the continuous and large-scale analysis of land use changes and their implications at the provincial level remains underrepresented in the extant literature. This methodological and conceptual discrepancy has been demonstrated to have a significant impact on the development of effective strategies for sustainable resource management and environmental impact mitigation, as well as on the planning process itself. This study utilizes an analytical approach, examining Landsat satellite imagery from 2004 to 2024, with the objective of accurately identifying changes in land use patterns in Tehran. The study further seeks to assess the ecological and social consequences of these changes. The findings of this study are expected to offer actionable insights that will inform enhanced resource governance and promote increased urban sustainability.

The objective of this research is to examine land use changes in the Tehran Metropolis between 2004 and 2024 and address existing research gaps in the region. The present study employs a combination of contemporary RS techniques, including GEE and GIS. The specific objectives of the research are as follows: The following three points will be examined in this study: Firstly, the use of multi-temporal satellite images in GEE to examine the extent, direction, and forms of land use changes in the Tehran metropolis; secondly, the detection of changes between land uses across different periods; and thirdly, the assessment of the ecological and ecosystem impacts of land use changes.

2. Materials and methods

2.1. Study area

The present research was conducted in Tehran Province, Iran, which has an aerial extent of approximately 19,177.8 km^2 (see **Figure 1**). Tehran, as the country's primary nexus of politics, economics, communication, and services, is acutely affected by ecological and environmental changes. The city is confronted with a range of challenges, including overpopulation, concentrated activities, extensive construction, and physical expansion of urban centers, which are contributing to the degradation of its natural ecosystem. Consequently, the depletion of ecological resources and environmental hazards have rendered the study area unstable. The presence of a variety of ecosystem services in the city has resulted in diverse environmental qualities. The central and southern parts of Tehran, which are located at a greater distance from the mountains and closer to the desert, are characterized by low, flat terrain. These areas are characterized by constrained horizontal visibility, deficient natural ventilation, and elevated levels of air pollution. Furthermore, these regions are confronted with a number of challenges, including limited annual rainfall, the occurrence of road flooding, and the experience of extremely hot summers [43].

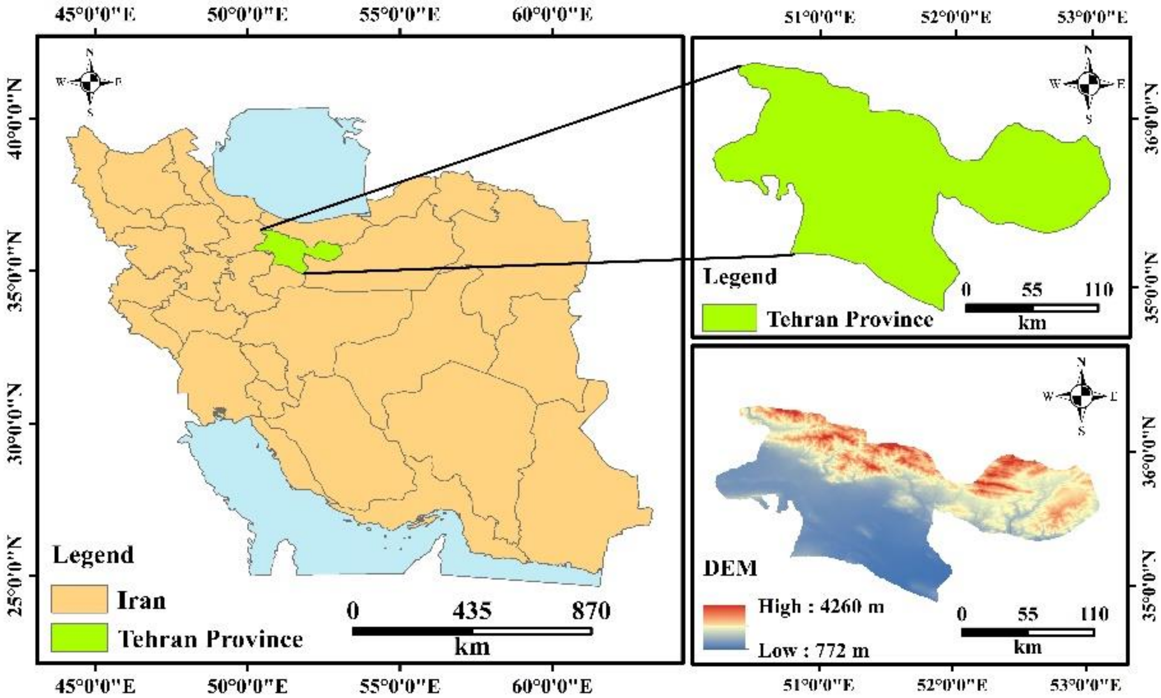

Figure 1. Location of Tehran Province in Iran.

2.2. Land use classification

GEE is a web-based platform for geospatial analysis that facilitates informed decision-making and sustainable land use management by monitoring surface changes due to natural and anthropogenic factors [22]. The detection of land use change plays a crucial role in the monitoring of these changes and the assessment of their environmental impacts. The advent of RS technology and cloud computing platforms has given rise to a plethora of tools capable of processing substantial quantities of spatial data with great expediency and efficacy. GEE, a prominent example of such a tool, is a cloud-based platform that has caused a major shift within the field of RS by providing access to satellite imagery and other spatial data [44].

For the present study, satellite images with a 30-meter spatial resolution from Landsat-5 (TM) and Landsat-8 (OLI) were utilized. The research considered multi-temporal Landsat satellite images from 2004 to 2024. For the purpose of classification, exclusively cloud-free images were employed directly from the GEE platform using command-line code. Following the retrieval of the Landsat 5 and 8 images, they were subjected to spatial filtering using the shapefile of the study area and temporal filtering. The present study evaluated the data for all periods within a single season (summer) in order to enhance the detection of ecological spaces.

For the purpose of creating land use classification maps, composite images of bands 2, 3, 4, 5, 6, 7, and 10 from Landsat 8 and bands 2 to 7 from Landsat 5 were selected. Approximately 1000 samples were collected on an annual basis for the purpose of classifying four distinct categories: urban areas, vegetation cover, barren land, and water bodies. These samples were then subjected to a supervised classification process. The random forest (RF) classifier algorithm was utilized in the supervised classification process of the GEE algorithm database to extract different land use classes. The RF algorithm has been demonstrated to be effective in preventing errors such as data noise and overfitting, thereby offering significant advantages for the classification of land cover data. Moreover, the efficacy and precision of this algorithm have been demonstrated to exceed those of alternative methods when implemented on larger scales [45].

2.3. Accuracy assessment

The process of evaluating the precision and dependability of classification outcomes is referred to as an accuracy assessment. This process involves the comparison of the classified data with the actual classes shown in the ground truth data. This comparison provides a precise evaluation of the classification performance by highlighting the correct and incorrect areas between the two datasets. The accuracy assessment process involves several steps, including the collection of ground truth data, the calculation of overall accuracy, the determination of user and producer accuracy for each land use class, and the computation of the Kappa coefficient. Each of these steps is essential for evaluating the accuracy of land use classification results and provides clear information about the performance of the classification algorithm [46]. For the purposes of this study, authentic satellite imagery data from Google Earth was utilized for the purpose of validating the classification results.

2.4. Change detection

In order to effectively identify and measure land use changes, it is first necessary to select an appropriate change detection method. A range of change detection algorithms is at the researcher's disposal, including object-based change detection, image differencing, and post-classification comparison. The selection of the most appropriate algorithm is contingent upon the study objectives, the availability of data, and the characteristics of the images in question [14]. Following the validation of the generated maps, the subsequent step involves the utilization of additional remote sensing and GIS technologies, including ArcMap and TerrSet, to enhance the detection of land use changes [47]. For the purpose of analysis, the area of different land uses in each period is determined in square kilometres (km^2). Furthermore, the CrossTab command in TerrSet software was utilized to identify alterations between diverse land uses.

3. Results and discussion

3.1. Land use dynamics

The accuracy of the land use maps generated using the GEE platform was evaluated through the Kappa coefficient. The Kappa values for the years 2004 and 2024 were 0.82 and 0.87, respectively, indicating a high level of classification accuracy in both temporal instances. Furthermore, the overall accuracies of the maps were calculated as 86.89% for 2004 and 90.79% for 2024, reflecting a notable improvement in classification performance over the study period. In 2004, the built-up class exhibited the highest classification accuracy, whereas in 2024, the barren land class demonstrated the most accurate delineation. Conversely, the Water Body class exhibited the poorest accuracy in both years, a phenomenon that can be attributed to the spatial resolution limitations of Landsat imagery and the dispersed nature of such features within the study area. Please refer to **Table 1** for further details.

Table 1. The classification accuracy of different land uses.

Year	Land use	Built-up	Vegetation	Barren	Water body	Total	Accuracy assessment
2004	Built-up	57	2	2	1	62	91.94
	Vegetation	8	81	6	1	96	84.38
	Barren	2	6	96	4	108	88.89
	Water body	2	0	6	31	39	74.49
	Total	69	89	110	37	305	86.89
2024	Built-up	89	0	0	8	97	91.75
	Vegetation	0	79	2	1	82	96.34
	Barren	0	0	81	2	83	97.59
	Water body	2	0	13	27	42	64.29
	Total	91	79	96	38	304	90.79

The land use maps of Tehran Province for the period 2004 to 2024, presented in **Figure 2**, were generated using the GEE platform and classified into four major categories: The following categories are to be considered: built-up areas, vegetation cover, barren land, and water bodies. A detailed analysis of these maps, based on satellite imagery from the Landsat program, reveals significant changes in the regional landscape over the past two decades. These changes include rapid urbanization and substantial degradation of green and ecological spaces. The accelerated expansion of urban areas has had a substantial impact on the structure of land use, resulting in the conversion of significant areas of agricultural and vegetated land into anthropogenic uses. Tehran, a region undergoing rapid development, has experienced a growing dominance of artificial structures over a significant portion of its total area. This phenomenon carries profound implications for ecological sustainability and urban management.

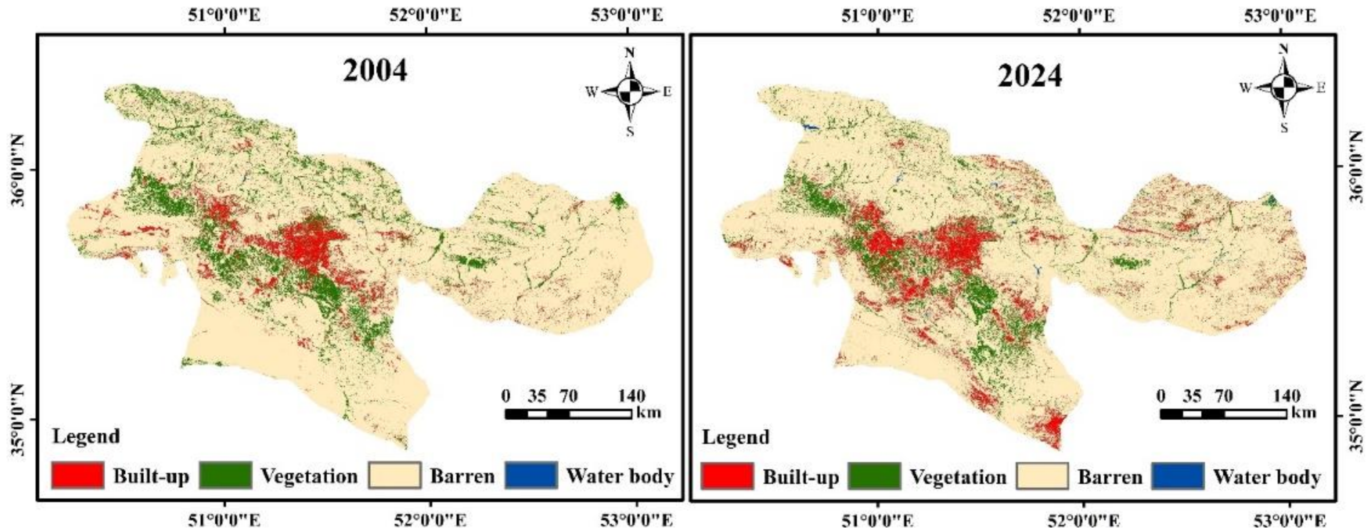

Figure 2. Spatial distribution of land use in 2004 and 2024 across the study area.

The land use analysis of Tehran Province for the year 2004 reveals a predominant distribution of barren land, which covers an area of 15,610.3 km^2, accounting for 81.39% of the total area. Vegetation cover ranked second with 2028.4 km^2 (10.58%), followed by built-up areas occupying 1527.0 km^2 (7.97%). Water bodies, with an area of only 12.1 km^2 (0.06%), reflect the arid and semi-arid nature of the study region. This preliminary distribution underscores the prevailing ecological conditions and the constrained patterns of urban development that characterized that era. Statistical data concerning land use for the years 2004 and 2024, along with the corresponding changes, are presented in **Table 2**.

Table 2. Statistical information of area and changes in land use.

Land use	2004		2024		2004–2024	
	km^2	(%)	km^2	(%)	km^2	(%)
Built-up	1527.0	7.97	1814.5	9.46	+287.5	+1.5
Vegetation	2028.4	10.58	1570.1	8.19	−458.3	−2.4
Barren	15,610.3	81.39	15,735.8	82.05	+125.5	+0.7
Water body	12.1	0.06	57.4	0.30	+45.3	+0.2

The 2024 land use map estimates the area of barren and dry lands at 15,735.8 km^2, thus maintaining its status as the dominant cover at 82.05% of the total area. The area under consideration has undergone significant expansion, with an increase of 287.5 km^2 over a 20-year period. Presently, it encompasses an area of 1814.5 km^2, representing a 9.46% increase and ranking as the second most prevalent cover type. Vegetation cover exhibited the most significant percentage change, with a decrease of 2.4% to 1570.1 km^2, accounting for 8.19% of the total area. The area of water bodies increased to 57.4 km^2, covering 0.3% of the region.

3.2. Land use change analysis

In order to achieve a higher level of precision in the identification of transitions between different land use classes over the 2004–2024 period, the CrossTab function in the TerrSet software was employed. The graphical representation of these transitions, presented in **Figure 3**, visually illustrates the spatial transformation patterns. The results of this analysis indicate substantial changes in land use, particularly in areas adjacent to urban zones. The most prominent change patterns—distinguished by contrasting color combinations on the map—were predominantly observed in proximity to the Tehran metropolitan area, indicating a high intensity of land transformation driven by urbanization pressures in this region.

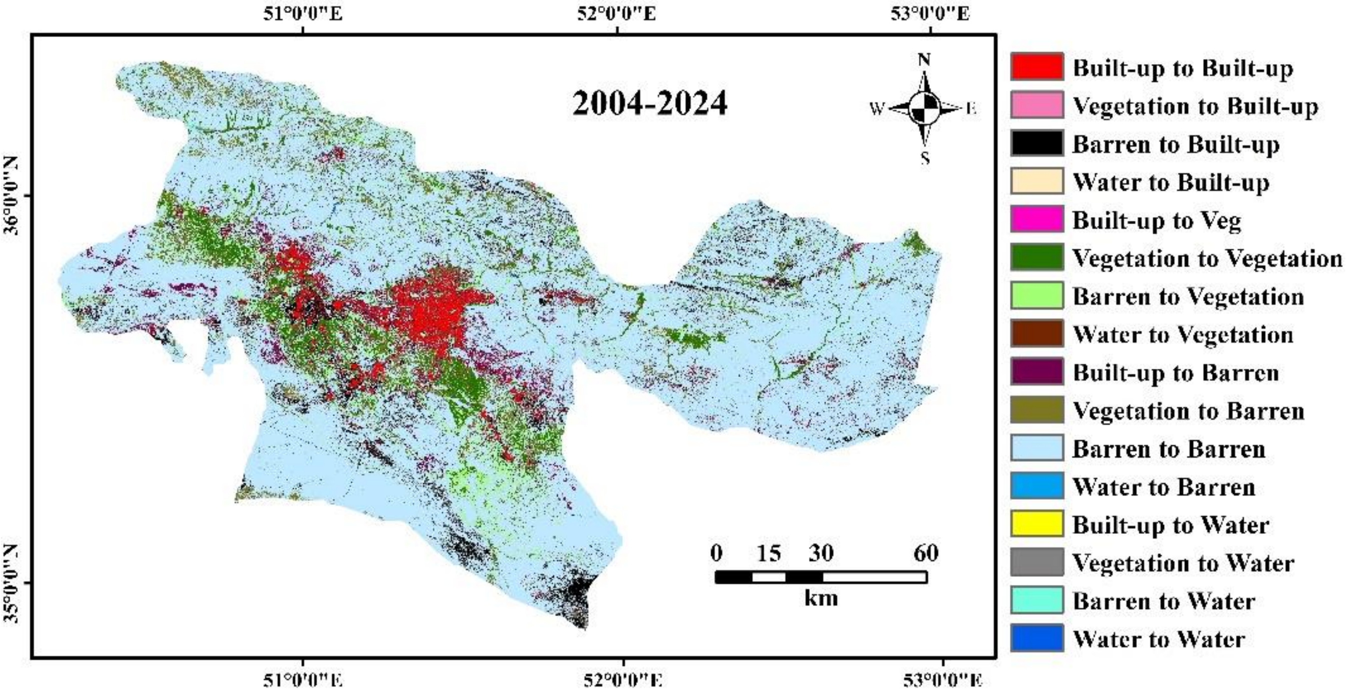

Figure 3. Changes among different land uses (2004–2024).

As illustrated in **Table 3**, the spatial analyses conducted using ArcMap software have enabled the derivation of area and percentage changes between different land use classes. The data indicates that the most significant transformations include the conversion of barren land to built-up areas, amounting to 1219.4 km^2 (6.4%), and the transition from vegetation cover to barren land, covering 1004.5 km^2 (5.2%). Other significant changes include the conversion of built-up areas to barren land (3.5%) and the reverse process, i.e., the transformation of barren land into vegetation cover (3.2%). The detailed results of these land use transitions are provided in **Table 3**.

Table 3. Area and percentage of changes between land uses in the period 2004–2024.

Changes	Area (km^2)	%
Built-up to Built-up	518.8	2.7
Vegetation to Built-up	76	0.4
Barren to Built-up	1219.4	6.4
Water body to Built-up	0.2	0.0
Built-up to Vegetation	22.3	0.1
Vegetation to Vegetation	931.2	4.9

Table 3. (*Continued*).

Changes	Area (km^2)	%
Barren to Vegetation	615.4	3.2
Water body to Vegetation	1.2	0.0
Built-up to Barren	665.1	3.5
Vegetation to Barren	1004.5	5.2
Barren to Barren	14,061.3	73.3
Water body to Barren	4.9	0.0
Built-up to Water body	1.5	0.0
Vegetation to Water body	16.7	0.1
Barren to Water body	33.3	0.2
Water body to Water body	5.8	0.0

In order to provide a clear and effective visual representation of land use changes over the 2004–2024 period, a Sankey diagram was employed, as illustrated in **Figure 4**. The diagram illustrates the utilization of distinct colors to differentiate the various land use classes for the two specified time points (2004 and 2024). The transitions from each class to the other three are depicted through colored flow panels, with the thickness of each panel corresponding to the area of land converted. This visual technique facilitates an intuitive and precise understanding of the scale and spatial patterns of land use transformations. The approach has been demonstrated to enhance the analysis of spatial dynamics and to offer a more profound level of insight into the prevailing land use trends within the designated study area.

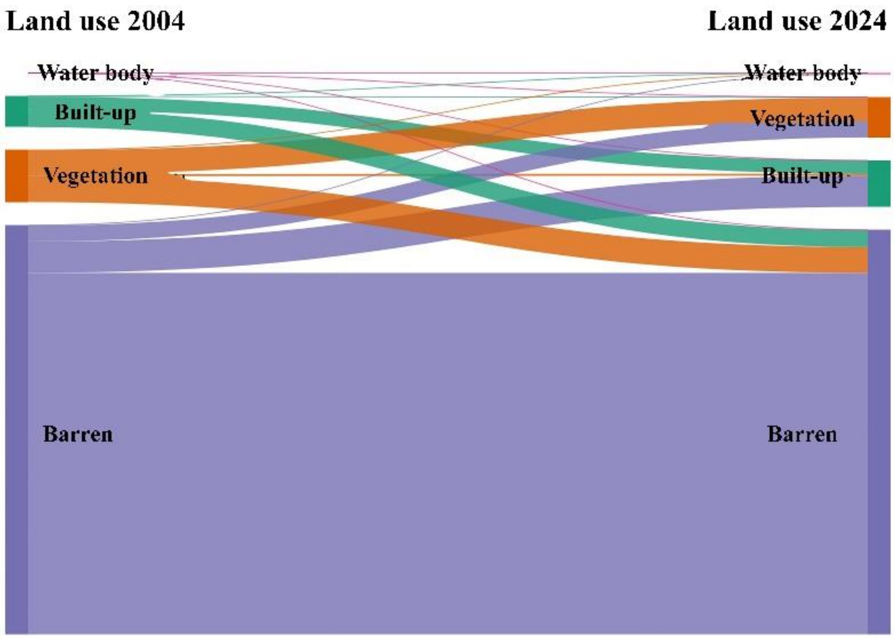

Figure 4. Revealing changes between different uses from 2004 to 2024 using a Sankey diagram.

3.3. Limitations, and future direction

The integration of GEE and GIS in this study has proven to be highly effective for continuous and high-resolution monitoring of land use changes, trend analysis, and data-driven decision support. However, several limitations should be acknowledged to provide a comprehensive understanding of the study's constraints. First, while Landsat imagery offers long-term historical records, its moderate spatial resolution may limit the precision of land cover classification, especially in heterogeneous urban or agricultural landscapes. The presence of cloud cover further impacts data availability and quality, necessitating additional filtering or interpolation techniques for improved accuracy. Furthermore, the validation process could benefit from more extensive ground-truth data collection to enhance classification accuracy and reduce potential uncertainties. Additionally, the study did not incorporate high-resolution satellite imagery such as Gaofen-1 [48] or hyperspectral datasets [49], which could significantly enhance the level of detail in land use classification. Future research could explore the integration of Sentinel-2 imagery, which offers superior spatial and spectral resolution, thereby improving the reliability of analysis and overcoming some of the limitations associated with Landsat-based assessments.

Moreover, while this study focused on retrospective analysis, future investigations could extend to predictive modeling of land use changes under various environmental and policy-driven scenarios. The implementation of advanced simulation models such as CA-Markov would enable researchers to project future land use dynamics, incorporating nature-based solutions for sustainable planning and management. This approach would provide valuable insights for policymakers seeking to mitigate environmental impacts and optimize resource allocation [22]. By addressing these limitations and expanding research methodologies, future studies can further enhance the precision and applicability of remote sensing techniques for land use change analysis, ensuring more robust and policy-relevant outcomes.

4. Conclusion

The present study utilized state-of-the-art remote sensing technologies, encompassing GIS and the GEE cloud computing platform, to scrutinize the spatiotemporal dynamics of land use shifts precipitated by accelerated urbanization in Tehran Province during the period 2004–2024. The analysis of Landsat satellite imagery, in conjunction with the application of TerrSet software, has revealed a substantial increase in built-up areas by 287.5 km^2 (1.5%), primarily concentrated in the western and southern regions of the province. This expansion has occurred at the expense of significant reductions in vegetated areas (−458.3 km^2, or −2.4%) and increases in barren lands (125.5 km^2) and water bodies (45.3 km^2). Cross-tabulation analysis further indicated that the dominant land use transitions involved the conversion of barren lands to built-up areas (1219.4 km^2) and vegetated areas to barren lands (1004.5 km^2). The classification accuracy was validated by high overall accuracy (90.79% in 2024) and Kappa coefficients (0.87 in 2024), confirming the reliability of the results.

A synthesis of the present research's findings indicates a strong congruence with those of preceding studies. For instance, Khazaei et al. [50] reported a marked decline in orchards and green spaces concomitant with the expansion of residential zones in Tehran over the past two decades, findings that are consistent with our own observations regarding vegetation loss. In a similar vein, Khodadad [51] documented a considerable increase in urban areas in District 15 of Tehran over the past 30 years. At the regional scale, Azizi et al. [52] in Shahriar and Azizi and Dehghani [53] in District 22 of Tehran highlighted the role of infrastructure development and socio-economic drivers as the main contributors to the transformation of agricultural and barren lands into built-up areas [52]. These findings are corroborated by the extensive barren-to-urban conversions identified in this study. This finding is corroborated by additional research by Veisi Nabikandi and Shoja [44], which also confirmed a considerable decline in vegetation cover and proliferation of impervious surfaces during similar periods. Research undertaken from a global perspective, including studies such as that by Koko et al. [30] in China, has emphasized the dominant role of urban expansion in land use changes. This international consistency enhances the ecological validity of the present results and suggests that the trends observed in Tehran reflect broader global challenges related to urbanization and environmental pressures.

The consequences of these transformations extend beyond physical land changes and encompass substantial ecological and social dimensions. The loss of vegetation and its replacement with barren lands signals a number of threats, including biodiversity loss, increased surface runoff, deteriorating air quality, and the intensification of the urban heat island effect. The expansion of built-up areas, at the expense of ecosystems and natural resources, necessitates urgent intervention by urban planners and policymakers. The observed increase in water bodies, potentially attributable to dam construction or hydrological alterations, also points to complex changes in regional water cycles that merit further investigation.

The study emphasizes the necessity for comprehensive and sustainable land use planning strategies in the Tehran metropolitan area. The strategic utilization of remote sensing technologies, the conservation of remaining green spaces, the control of urban sprawl, and the redevelopment of degraded lands have the potential to significantly enhance the region’s ecological and social resilience. It is recommended that subsequent research endeavors utilize radar data, higher-resolution imagery, and predictive modeling based on machine learning in order to broaden both the scope and the precision of the analysis.

Author contributions: Conceptualization, FS and BVN; methodology, BVN; software, BVN; validation, FS and BVN; formal analysis, BVN; investigation, FS; resources, FS and BVN; data curation, BVN; writing—original draft preparation, BVN; writing—review and editing, FS and BF; visualization, FS and BVN; supervision, BF; project administration, BVN; funding acquisition, FS. All authors have read and agreed to the published version of the manuscript.

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