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Analysis of Changes in Vegetation Index during the Rapid Urban Spatial Development Period (1990–2020) in Tehran Metropolis, Iran

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Abstract: Rapid urbanisation, economic growth, and urban spatial development in developing countries, such as Iran, have resulted in tremendous loss of green cover and associated ecological problems. Any effort to achieve sustainable urban development should be supported by recognising and evaluating the ecological health of vegetation cover. This study investigates vegetation cover reduction and changes in the Tehran Metropolis, Iran and identifies the most important factors influencing the observed changes. The aim of this study is two-fold: first, to assess the spatio-temporal changes in vegetation cover in Tehran between 1990 and 2020, and second, to identify the factors contributing to the changes. The Normalised Difference Vegetation Index (NDVI) is used as an indicator of green cover. The spatial and statistical data used in this study were extracted from Landsat satellite imagery and the last approved Master Plan of Tehran (2006). Geographically Weighted Regression (GWR) and geographical modelling methods were employed to analyse vegetation cover in all municipal districts of the Tehran metropolis. The results show that the vegetation density in the Tehran metropolis decreased significantly (from 38,936.80 hectares to 4663.23 hectares) between 1990 and 2020. The expansion of construction lands and the increase of population density were the most significant factors affecting the reduction in vegetation cover in Tehran. In contrast, the growth of industrial units in the urban areas of Tehran had no significant relationship with vegetation cover. The results of this study can help urban planners understand the significant drivers of vegetation loss and identify appropriate interventions to prevent it.

Keywords: vegetation index; NDVI; urban development; green cover; Tehran metropolis; Iran

Citation: Zenouzi, A.S.; Yenneti, K.; Teimouri, R.; Abbasiyan, F.; Palme, M. Analysis of Changes in Vegetation Index during the Rapid Urban Spatial Development Period (1990–2020) in Tehran Metropolis, Iran. *Atmosphere* **2022**, *13*, 2010. https://doi.org/10.3390/atmos13122010

Academic Editor: Rohinton Emmanuel

Received: 27 October 2022
Accepted: 22 November 2022
Published: 30 November 2022

1. Introduction

1.1. Background

Vegetation cover is essential to urban ecosystem services [1] and has significant environmental, aesthetic, recreational, health and economic values in cities [2,3]. It plays a vital role in biosphere activities and terrestrial ecosystem operations by affecting hydrology, climate, and nitrogen and carbon cycles [4].

In urban areas, vegetation cover is considered a part of land use development and planning [5] and can contribute to heat island mitigation [6–8], air pollution reduction [9,10], and enhanced quality of human life. However, urban development in different ecosystems affects vegetation cover [11]. Urbanisation often replaces natural features such as green spaces and vegetation cover with dense built-up areas and roads [12,13]. This conversion of natural or semi-natural ecosystems to urban built-up or artificial ecosystems leads to a reduction in biodiversity and natural resources [14,15], an increase in environmental damages [16–18], and a disruption of ecosystem processes and structures [19,20]. Rapid urban growth and immense land-use alteration, particularly green space, can also pose significant challenges to sustainable urban development. In this context, it is important to pay attention to the relation between an increase in urban construction and a reduction in open and green spaces.

1.2. Urban Development and Green Spaces

Understanding the spatial patterns of vegetation cover changes is a fundamental aspect of urban sustainability [21] and can help urban planners and decision-makers identify drivers of land cover changes and take necessary actions to prevent the changes. A strong correlation between urban land use planning and ecological issues was recognised as early as the 1970s via the commencement of the environmental movement [22].

Over the past few decades, researchers around the world have monitored the impact of urban development on vegetation and ecosystems using different techniques and methods [11,21,23,24], and concluded that the relation between urban development and urban vegetation cover is complicated [23,25]. A study on the spatio-temporal patterns of Normalised Difference Vegetation Index (NDVI) in Delhi indicated a significant decline in vegetation with the recent expansion of built-up areas [26]. Interestingly, Li et al. (2020) found that the vegetation cover in the central parts of Beijing increased with rapid urbanisation, while the green cover in the suburbs degraded significantly. A study on the spatio-temporal changes (over 33 years) of NDVI in Mongolia shows that a decrease in vegetation cover is almost equal to an increase in area. Climate change and changes in livestock numbers were found to be the major factors [24].

Several studies also suggest that urban development and population growth can have significant negative impacts on ecosystems and replace pristine forests, pastures, and agricultural lands with built-up areas [27,28]. According to Emberson et al., (2001), increasing pollutants from industrial activities in cities of industrialised countries are adversely affecting the health and productivity of urban vegetation cover. However, the ecological effects of the spatial development of human settlements vary across different spatial scales (e.g., city, region and nation) [29,30], and depend on different site-specific factors (e.g., climate, topography, landscape, demography, and economy) [11,31]. Assessing and monitoring ecological sustainability at different spatial scales is a challenge for most societies [29,30].

1.3. Remote Sensing of Vegetation Cover

Cities around the world are now seeking integrated solutions to address fundamental environmental problems and create more sustainable societies [32]. Realistic knowledge of urban land cover is important for optimising urban vegetation planning, urban management, improving air quality, and mitigating the effects of global climate change [33]. Accurate mapping of urban land cover can also provide the data necessary to understand urban ecosystems in the best possible way and help improve the urban environment and the human quality of life [34].

A combination of Remote Sensing (RS) and Geographic Information System (GIS) tools are some of the commonly used monitoring and mapping methods for analysing changes in vegetation cover and urban green spaces [35]. These tools have benefitted different urban planning and development research domains interested in the evolution of urban areas, exploring changes in vegetation cover and identifying interventions to mitigate the changes [36–38]. In particular, RS is an ideal tool for studying the spatio-temporaral dynamics of large-scale vegetation [38].

Satellite systems with high-resolution and multispectral sensors can provide valuable data for monitoring and mapping vegetation cover changes in urban areas. Satellite systems provide multispectral image data with high radiometric resolutions (1.65 m–4 m spatial resolutions) [39]. Satellite imagery methods have been applied to investigate issues such as urban forms, economic development, and vegetation cover (index) on regional to global scales [40,41].

Vegetation indices are based on two or more spectral bands [42] and are valuable tools for extracting vegetation eco-physiological, biochemical, and physical characteristics [43]. NDVI is one of the most widely used vegetation indices [44,45]. Its application in evaluating and monitoring vegetation changes has been well documented over the past two decades [46–49].

1.4. Current Study

As the first manifestation of modern urban planning in Iran, the city of Tehran has undergone extensive ecological and green infrastructure changes under the influence of capitalism, mass migration and industrial development. In recent years, the city has experienced increasing environmental problems due to rapid physical development and massive changes in land-use (conversion of green and agricultural lands to build-up lands). Therefore, studying land-use changes and the underlying drivers can support urban management and planning, improve the vegetation index and renew ecological resources. This study is guided by two research questions: (i) What changes have occurred in the vegetation index in the Tehran metropolis from 1990 to 2020? and (ii) Which factors are effective in the process of changes in the vegetation index in Tehran? One of the main contributions of this research is that it combines descriptive (Landsat satellite imagery and Tehran Master Plan) and spatial analysis methods (Geographical Weighted Regression (GWR) model) to achieve the research objectives.

2. Methodology

2.1. Study Area

Tehran province has a population of about 13 million and an area of 18,814 square kilometres (km^2). The city of Tehran is geographically located at 51°17′ to 51°23′ east longitude and 35°36′ to 35°44′ north latitude in the Tehran province. It is the administrative and political capital of Iran and has a population of about 8 million. The metropolis stretches between the Alborz Mountains range in the north and desert valleys in the south of Iran (Figure 1). It is the 38th most populous city in the world and has an area of 612 km^2 [50,51];

The city of Tehran has a population density of about 10,700 to 11,000 people per km^2 and is divided into 22 municipality districts [52]. Approximately, 11.5% of the country's total population, 24% of the country's population with higher education, 26% of the Gross Domestic Product (GDP), 14% of the country's development budget, 26.5% of the current government budget, 38% of the cultural and educational facilities, and 26% of the medical facilities are concentrated in the city of Tehran [53].

A review of the Tehran metropolis' urban land use map shows that residential land use (28.8%) accounts for the highest proportion of the city land use. Roads, green space, and urban services account for 18.6%, 11.4% and 8.1% of the total urban land use, respectively [54].

2.2. Research Methods

This study is conducted in three stages (Figure 2). All stages contribute to the aim of this study, which is to investigate changes in the vegetation cover between 1990 and 2020 and the underlying factors influencing the physical expansion of the Tehran metropolis. In this study, two data sources (satellite and geospatial data) and documents related to Tehran metropolis planning programs, (including Master Plan) were used.

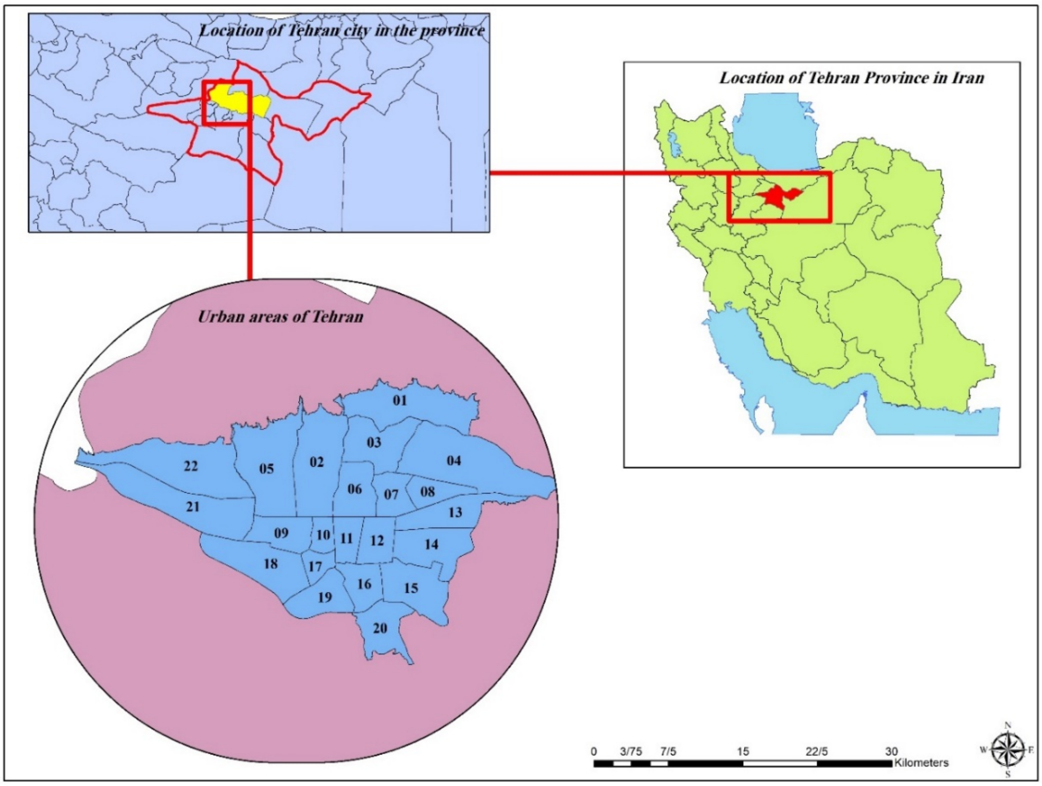

Figure 1. Location of Tehran metropolis.

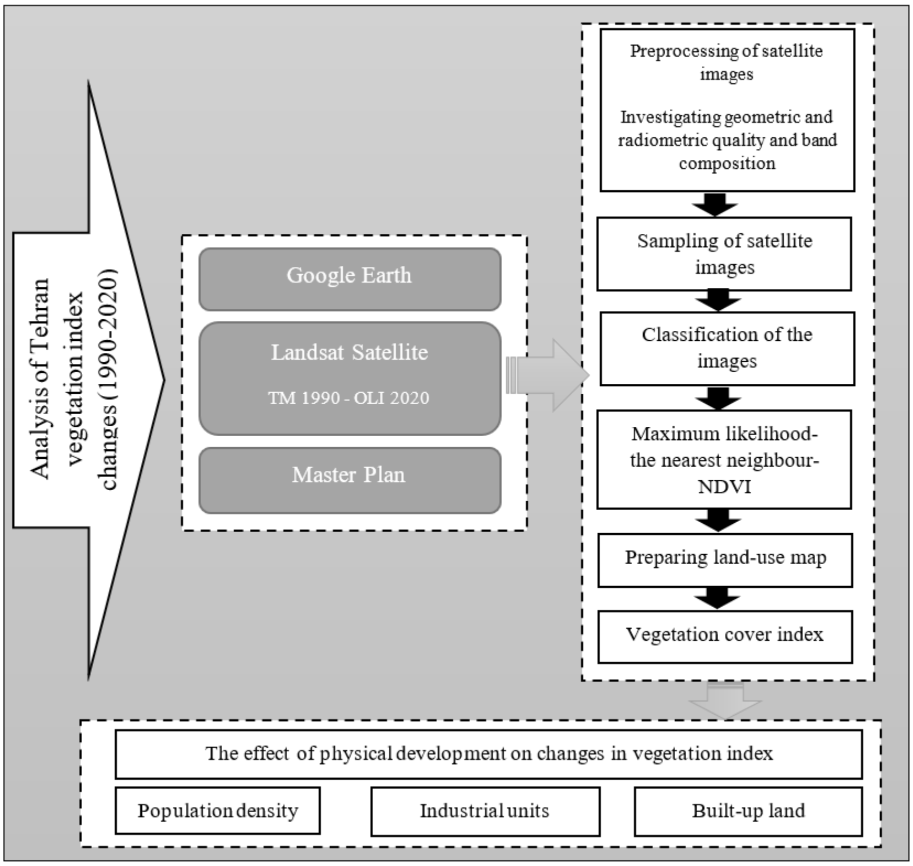

Figure 2. Data Analysis.

- Stage 1

To discover changes in vegetation cover over the period 1990–2020, satellite imagery is required. Therefore, the Landsat Satellite multispectral images (TM sensor) from 22 June 1990, and the OLI/TIRSS multispectral images from 14 May 2020, were used. The features of the extracted images are shown in Table 1. All satellite images were extracted from the United States Geological Survey (USGS) website (https://earthexplorer.usgs.gov/, accessed on 10 March 2022). Raw satellite images were pre-processed to fix any common errors (e.g., geometric and radiometric correction errors) [55] that would prevent them from being used directly as flattened maps [56]. Geometric corrections of satellite imagery can remove deviations, improve image quality, and make the extracted images usable [57]. Topographic map (scale of 1:50,000) [58] and Google Earth map 2020 were used for geometric correction of satellite imagery. Using the Google Earth map, several ground control points were selected from the study area. After eliminating the points with large errors, 11 points in 1990 and 15 points in 2020 with a proper distribution were selected. The final selected points are mostly from street intersections, main roads, and waterways [59,60].

Table 1. Landsat 5 and 8 satellite images between the years 1990 and 2020.

No	Shooting Date	Satellite	Sensor	Bands Number	Format
1	22 June 1990	L5	TM	8	TIFF
2	14 May 2020	L8	OIL/TIRSS	11	TIFF

A first-order transformation equation was used to convert the coordinates of the corrected image (1990 image) to the uncorrected image (2020 image). The Nearest Neighbour method was used to resample the values of uncorrected image pixels. Finally, the TM sensor (1990 image) was georeferenced with an RMSE error of 0.34, while the OLI sensor image (2020 image) was georeferenced with an RMSE error of 0.36. Radiometric Calibration in ENVI software was used to fix radiometric and atmospheric errors, resulting in a significant increase in image resolution.

To determine the study area, the corrected satellite images were separated from the selected images in the ENVI software environment in dimensions of 700 $\times$ 700 pixels (approx. 21 $\times$ 21 km).

The first step in the research process was dedicated to the calculation of the vegetation index, which was performed using the NDVI tool in ENVI software. The vegetation index is one of the RS spectral indices [61], and is calculated using the formula [62,63]:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{R})}{(\mathrm{NIR} + \mathrm{R})} \quad (1)$$

where, NIR is the near-infrared band, and R is the red band [64]. The higher the chlorophyll amount in the plant, the higher the index [65]. The values of the NDVI index are in the range between -1 and +1. Different values of the index represent different coverage. For example, values between 0.1 and 0.2 represent areas with low vegetation, values between 0.2 and 0.5 represent areas with medium vegetation, and values above 0.5 represent areas with rich and abundant vegetation. Water, snow, and ice have negative NDVI values, while soils have values less than 0.05 and clouds have values around zero [55].

Based on the values obtained in this study, the vegetation index classes were classified into six categories: no vegetation, very low to low vegetation, low to medium vegetation, medium to high vegetation, high to very high vegetation and abundance of vegetation. The vegetation cover index was calculated for both 1990 and 2020, and the changes in these two years were considered as the basis for evaluating the green space situation in the Tehran metropolitan area.

- Stage 2

In this stage, the status of built-up lands in 22 districts of the Tehran metropolis was analysed. After pre-processing the satellite imagery, appropriate colour combinations were selected to classify the land cover types in the study area for the two study periods (1990 and 2020). The composite tool in the Idrisi software was used to test different colour combinations. Finally, the colour combinations (R-7, G-4, B-2) and (R-4, G-3, B-2) were selected as appropriate colour combinations for display.

After finalising the colour combinations, the land cover types in the study area were classified using supervised classification and maximum likelihood methods in Idrisi software. Training samples were first collected in the form of polygons with a proper distribution of about 100 polygons per image, using the Tehran land use map, Google Earth, and processed images. In the end, four similar training samples (green lands, barren lands, built-up lands and water areas) were selected for two images (1990 and 2020), respectively, out of which the built-up lands were investigated in this study. The images were then classified using supervised classification method. Then, Maximum Likelihood Method in the Idrisi software was used to classify the images and generalise the samples to the entire study area. The Maximum Likelihood Method is one of the widely used remote sensing image classification methods [66].

- Stage 3

After determining the vegetation cover index (Stage 1) and built-up land growth trend (Stage 2), the influence of three variables (built-up, the population density and the extent and distribution of industrial units in urban areas) on the vegetation index was studied using a Geographically Weighted Regression (GWR) model. Data related to industrial units and population density were collected from the Tehran Municipality website (2020), while information related to industrial units was collected from the Tehran Master Plan.

Geographically Weighted Regression (GWR) model examines the spatial relationship of variables. GWR model is used in geographic sciences and other disciplines that use spatial data [67] and is more efficient than global regression methods. It can describe the information and relation between variables more precisely [68]. In this study, a GWR model was used to investigate the influence of variables on the change process of vegetation index. The main reason for using a GWR model in this study is to study the spatial nature of the variables, which influence each other spatially.

Equation (2) shows the diagonal weight matrix.

$$\mathrm{Wi} = \begin{bmatrix} \mathrm{Wi1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \mathrm{Win} \end{bmatrix}, \quad (2)$$

A GWR model forms for each i weight matrix. These weights vary for each i. The closer positions gain more weight. The relationship between two variables (positive or negative and strong or weak) can be reflected in space by the GWR technique [69]

3. Results

3.1. The Trend of Vegetation Index Changes in Tehran Metropolis (1990–2020)

In this study, the vegetation index classes of the Tehran metropolis over the past three decades (1990–2020) were analysed (Table 2). The factors influencing the trends were obtained through a GWR model. The total number of cells in the vegetation index map is 690,878. The commonly used vegetation classifications were used to show changes and coefficients of the vegetation cover (Figure 3).

Table 2. The portion and percentage of vegetation index classes in the Tehran metropolis, 1990 and 2020.

SI.No	Vegetation Classes	1990		2020	
		Percentage	Number of Cells	Percentage	Number of Cells
1	No vegetation cover	1.77	12,437	28.22	13,364
2	Very low to low vegetation cover	4.57	31,778	36.95	33,624
3	Low to medium vegetation cover	9.84	68,413	17.70	65,640
4	Medium to high vegetation cover	21.18	147,916	9.61	147,916
5	High to very high vegetation cover	34.46	235,558	5.00	235,558
6	Abundance of vegetation cover	28.17	194,776	2.49	194,776
	Total	100.00	690,878	100.00	690,878

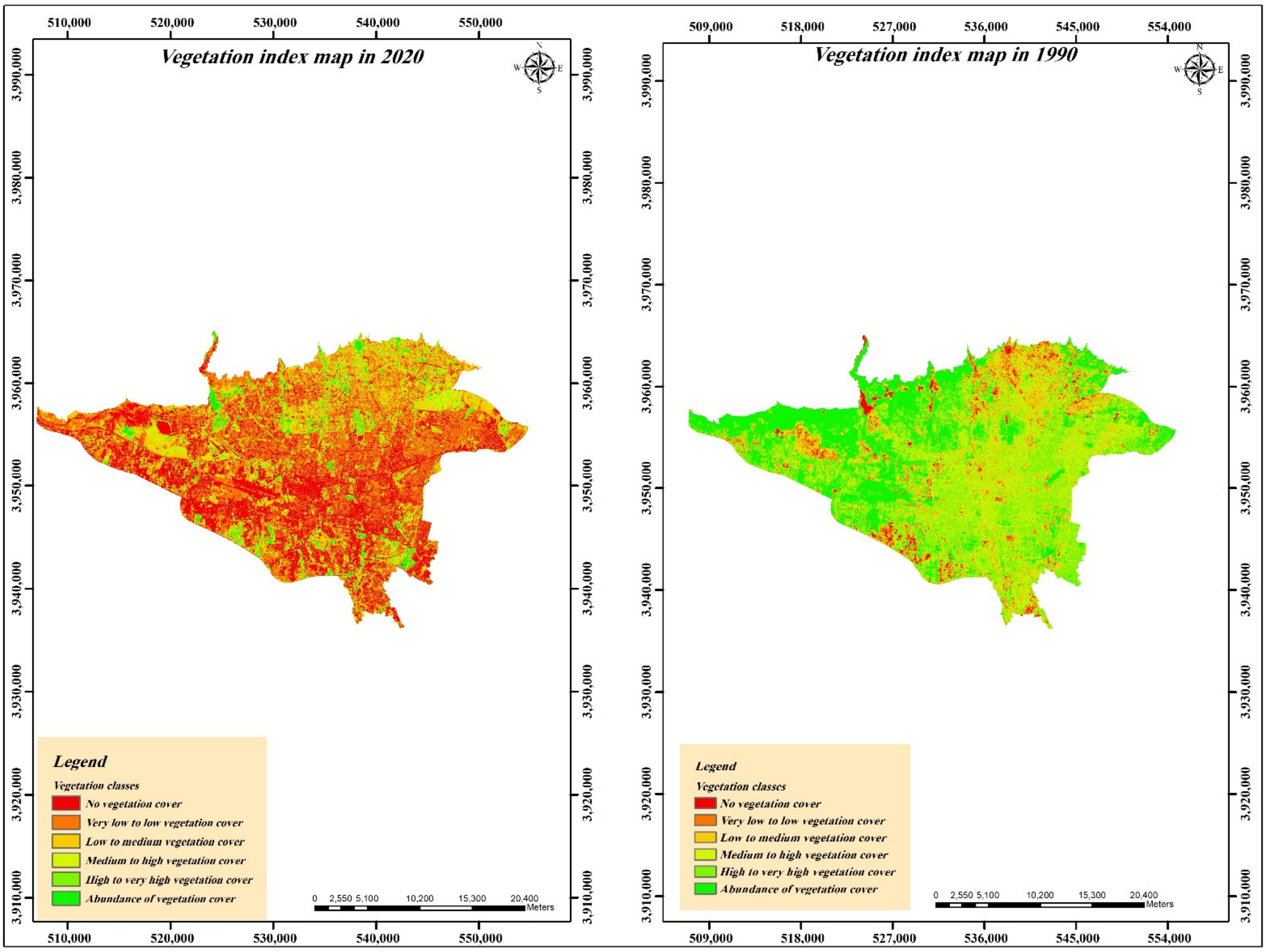

Figure 3. Vegetation index map of Tehran metropolis in 1990 and 2020.

High to very high vegetation cover (34.46%) accounted for the highest share of cells, followed by abundance of vegetation cover (28.17%). The lowest share was occupied by no vegetation cover (with 1.77%), followed by very low to low vegetation cover (4.57%). The abundance of vegetation cover class was mainly concentrated in the northern and north-western parts of the Tehran metropolis.

Over the past three decades, the study area has shifted from green lands to lands without green cover. In other words, the expansion of the built environment has intensified.

From 1990 and 2020, the categories of no vegetation cover, abundance of vegetation cover and medium to high vegetation cover showed an inverse growth pattern (Table 3).

Table 3. Change of vegetation index classes in the metropolis of Tehran between 1990 and 2020.

Vegetation Classes	Area in 1990 (Hectares)	Area in 2020 (Hectares)	Area Changes (Hectares)
No vegetation cover	1102.81	17,545.7	16,442.89
Very low to low vegetation cover	2841.73	22,971.45	20,129.72
Low to medium vegetation cover	6121.43	11,009.18	4887.75
Medium to high vegetation cover	13,167.79	5976.21	−7191.58
High to very high vegetation cover	21,424.1	3113.26	−183,108
Abundance of vegetation cover	17,511.98	1549.97	−15,962

In the 1990s, the percentage of the area without vegetation cover was less than 2%. By 2020, the area without vegetation cover increased to more than 28%. An opposite trend was observed in the abundance of vegetation cover class. The most prevalent type of vegetation cover in the 1990s was high to very high vegetation cover (34%). However, in 2020, very low to low vegetation cover (37%) was the dominant type of vegetation class.

Furthermore, an analysis of the spatial variation of vegetation classes in 22 districts of the Tehran metropolis revealed significant fluctuations in the area and number of vegetation parcels over the past 30 years. For example, the northern and western parts of the metropolis had comprehensive vegetation cover at the beginning of the period. However, by the end of 2020, a significant portion of those lands had disappeared.

On the one hand, the vegetation index changes in the western, northern, and southern peripheries of the Tehran metropolis were more significant than in other areas. In central Tehran, vegetation cover had decreased intensely. This is indicated by changes in districts 1, 2, 3, 5, 21 and 22. In 2020, three vegetation types namely medium-high, high-very high and abundant) experienced negative growth in these districts. In general, this situation indicates a reduction in vegetation cover and non-ecological development patterns throughout the Tehran metropolis.

3.2. Factors Influencing the Reduction of Vegetation Cover in Tehran Metropolis, 1990–2020

This section analyses the factors affecting the vegetation cover changes in the Tehran metropolis based on three variables: construction land, population density, and extent of industrial units.

The results of construction land are presented in Table 4 and Figure 4. Data for this variable were obtained through land cover maps extracted from Landsat satellite imagery (1990 and 2020). Between 1990 and 2020, the spatial changes in districts 21 and 22 were complex and the development of construction land was the most significant. About 1520 and 2.318 hectares of constructed land were added to the two districts, respectively.

Most of the changes in construction land occurred in the northern, north-western, western, southwestern, and southern parts of the Tehran metropolis. It is worth noting that the central districts (7, 8, 9, 11 and 12) experienced negative construction growth, indicating that Tehran metropolis has shifted from endogenous to exogenous growth over the past 30 years.

Another independent variable examined in this study is population density. Demographic data (2006–2018) related to the Tehran metropolitan area were obtained from the websites of the 22 district municipalities and the Statistics Center of Iran (Table 5). Due to data availability issues, this study considered population density data from 2006–2018 (Table 6).

Table 4. The area of constructed lands and its difference in the districts of Tehran metropolis in the period of 1990–2020.

Districts	Area in 1990	Area in 2020	Difference (Hectare)	Districts	Area in 1990	Area in 2020	Difference (Hectare)
1	364.3	1206.5	842.2	12	1502.3	1437.26	−65.04
2	1720.3	2698.4	978.1	13	1050.2	1137.14	86.94
3	925.3	1275.6	350.3	14	1474.6	1697.7	223.1
4	2498.5	3478.14	978.54	15	1903.4	2098.7	195.3
5	1389.15	3031.15	1642	16	1177.5	1222.2	44.7
6	1564.3	1561.8	−2.5	17	713.3	710.43	−2.87
7	1343.9	1267.6	−76.3	18	1624.8	2524.4	899.6
8	1210.4	1127.5	−82.9	19	654.8	1307.46	652.66
9	1518.5	1382.4	−136.1	20	1019.3	1681.6	662.3
10	769.6	767.9	−1.7	21	2258.19	3778.7	1520.61
11	1116.5	1081.61	−34.89	22	309.2	2627.7	2318.5

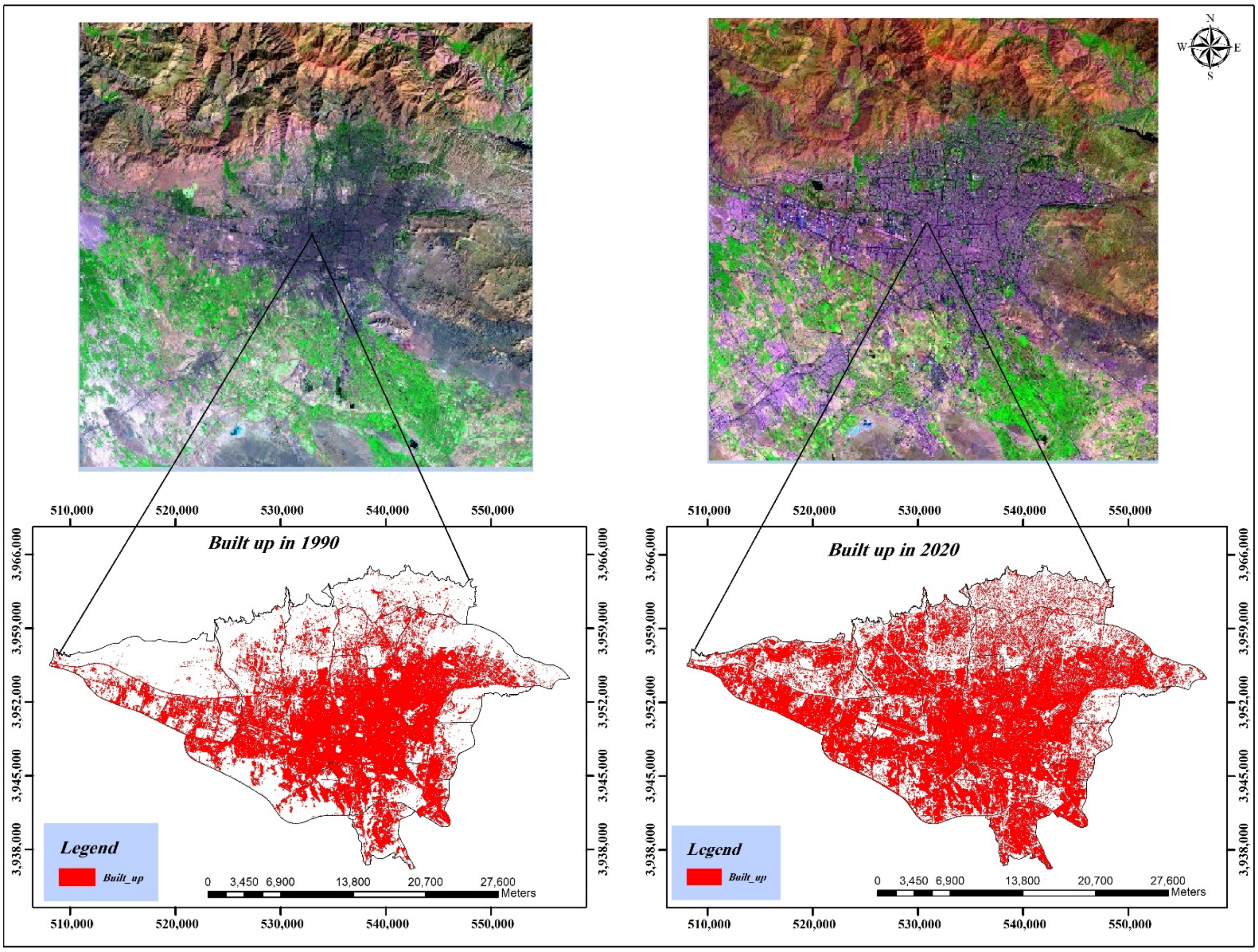

Figure 4. Satellite images and the growth trends of the constructed lands in the metropolis of Tehran for the periods 1990 and 2020.

Table 5. Demographic indices/population of 22 municipality districts of Tehran metropolis.

District	Population of 2018	Population of 2006	Districts' Areas (Hectare)	District	Population of 2018	Population of 2006	Districts' Areas (Hectare)
1	522,526	249,676	4.36	12	24,143	189,625	197.59
2	721,964	458,089	41.36	13	244,516	245,142	132.88
3	327,275	259,019	128.84	14	507,783	394,611	62.32
4	946,728	663,166	39.11	15	670,574	622,517	46.17
5	884,278	427,955	81.93	16	260,178	298,410	189.91
6	259,868	220,331	135.19	17	289,334	287,367	327.62
7	312,996	300,212	169.16	18	431,276	296,243	233.02
8	445,554	336,474	507.13	19	262,316	227,389	453.74
9	180,818	173,482	260.29	20	378,741	356,079	143.74
10	336,962	282,308	302.84	21	196,998	188,890	139.31
11	316,492	225,840	19.99	22	19,897	56,020	89.4

Source: [70].

Table 6. Demographic indices/density of 22 municipality districts of Tehran metropolis.

District	Population Density (Hectare) Year 2006	Population Density (Hectare) Year 2018	Population Density Difference	District	Population Density (Hectare) Year 2006	Population Density (Hectare) Year 2018	Population Density Difference
1	57,265.1	119,845.6	62,580.5	12	959.7	122.1	−837.6
2	11,075.6	17,455.6	6380	13	1844.8	1840.1	−4.7
3	2010.4	2540.16	529.7	14	6332.01	8147.8	1815.8
4	16,956.4	24,206.8	7250.4	15	13,483.1	14,524.01	1040.9
5	5223.4	10,793.07	5569.6	16	1571.3	1370	−201.3
6	1629.8	1922.2	292.4	17	877.1	883.1	6
7	1774.7	1850.3	75.6	18	1271.3	1850.8	579.5
8	663.5	878.8	215.3	19	501.14	578.1	76.96
9	6665	694.7	−5970.3	20	2477.2	2634.3	157.1
10	932.2	1112.7	180.5	21	13,559	1414.09	−12,144.9
11	11,297.6	15,832.5	4534.9	22	626.6	222.6	−404

Source: [70].

In 2018, districts 1, 2, and 5—located in the recently developed parts of the Tehran metropolis—had a high-density urban texture. Low-density areas were mainly concentrated in the western and southwestern parts of the metropolis (including districts 9, 22, and 19). Low-density clusters can also be seen in the central parts of districts 10 and 12 and the eastern parts of district 8, while high-density clusters appear in districts 22, 21, 5, 1 and 11. Statistical blocks located in the central and southern parts form the densest parts of the metropolis. Overall, population density appears to be increasing across the city.

Finally, the status of industrial land use was analysed. The inclusion of this variable is critical because its existence and extent can cause severe damage to the quantity and quality of green spaces and vegetation cover.

Table 7 shows the frequency, percentage, and per capita industrial use in different municipality districts of the Tehran metropolis. Data for this variable were extracted from the Master Plan of the Tehran metropolis. The areas with the most expansion of industrial units are located in the central and southern districts of the Tehran metropolis. Due to the economic and commercial nature of district 12 (the central part of Tehran), most of the small and medium industry activities (e.g., bags, shoes, clothing production and various accessories) were developed in this area.

A wide range of industrial activities such as the automotive industry, household appliances, activities related to the oil industry and refineries were concentrated in the southern districts of Tehran (Figure 5). These areas are known for their concentration of heavy industrial activity. In addition, industrial activities, such as pharmaceuticals and several automobile industries, were located along the Tehran-Karaj highway axis in district 21. In contrast, the central and northern districts of Tehran, including districts 1, 2, 3, 7, 11 and 19, had the lowest rates of industrial land use.

Table 7. Frequency and percentage of industrial units in Tehran municipality district.

District	Frequency of Industrial Units	Percentage	District	Frequency of Industrial Units	Percentage
1	121	0.98	12	3712	30.19
2	119	0.97	13	244	1.98
3	57	0.46	14	540	4.39
4	247	2.01	15	1587	12.91
5	162	1.32	16	1291	10.50
6	181	1.47	17	183	1.49
7	88	0.72	18	1091	8.87
8	1073	8.73	19	7	0.06
9	74	0.60	20	412	3.35
10	306	2.49	21	779	6.34
11	1	0.01	22	20	0.16

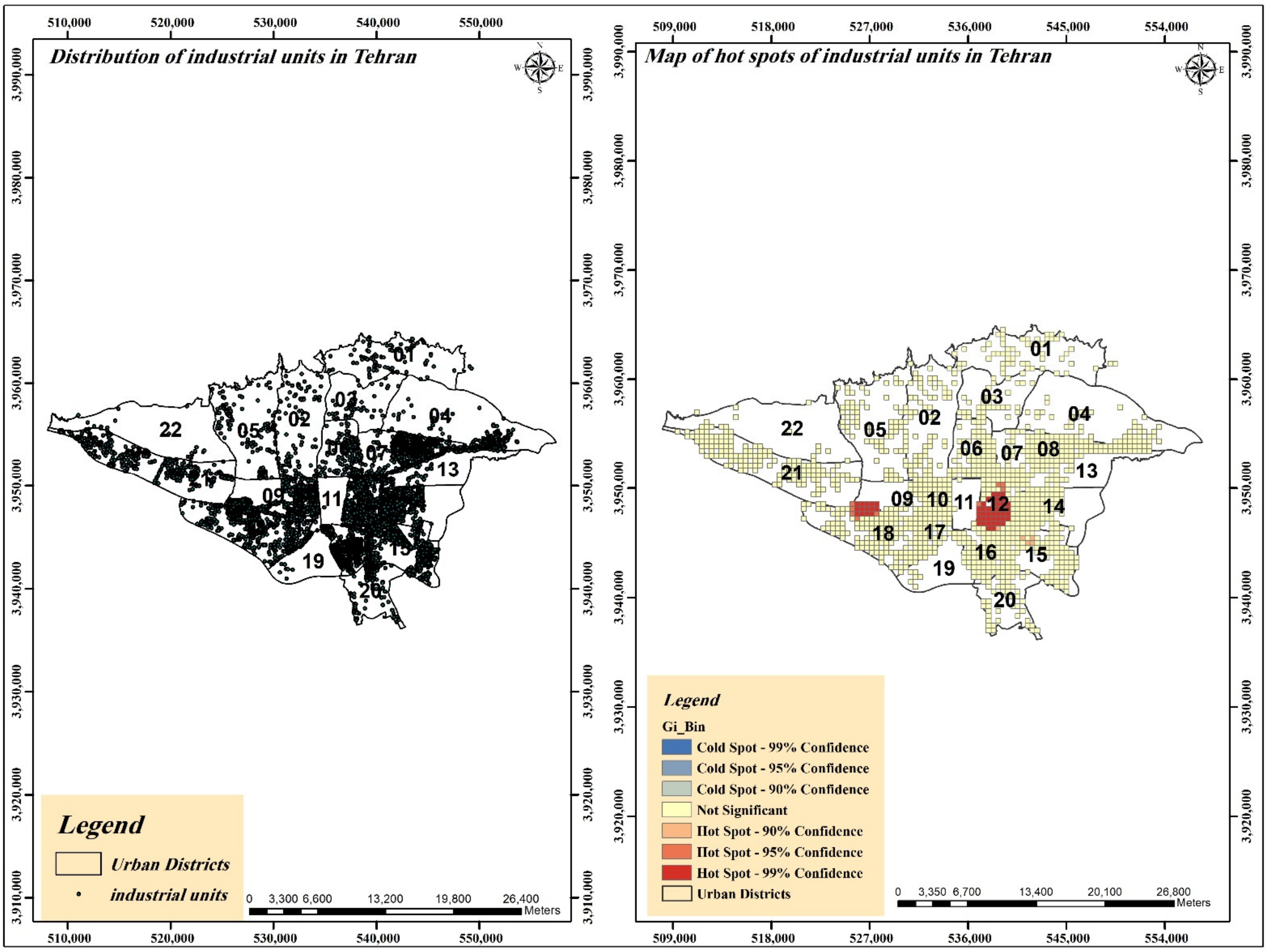

Figure 5. Status of distribution of industrial units in Tehran metropolis.

3.3. Analysing the Effects of Constructed Lands, Population Density and Industrial Units on Vegetation Cover

The interaction between different variables was studied assuming that all factors in an urban system are interdependent and that changes in each factor affect the function of the other factors. GWR model was used to study the spatial dependence of the dependent variable (changes in vegetation cover area between 1990 and 2020) on the independent variables (constructed lands, population density, and the extent of industrial units). The most important values in this model are R2 and adjusted R2, which indicate the accuracy of the model used. The closer the value is to 1, the better the descriptive variable can explain the changes in the dependent variable.

The calculated value of Local R2 for the construction land is between 0.576 and 0.757. The values of Local R2 for population density and industrial units are between 0.489 to 0.549 and 0.005 to 0.040, respectively. The values of construction land and population density show that these variables can clarify and explain the changes in the dependent variable. However, the value of industrial units indicates that this variable does not justify the changes in the dependent variable. Thus, there is no relationship between the extent of the industrial units and differences in vegetation cover in the Tehran metropolis.

Figure 6 shows the output layer of the GWR model with respect to residual values (ranging from −2.5> to <2.5). The value of the index is closer to or greater than 2.5, indicating an unusual distribution of residual values and a high spatial autocorrelation.

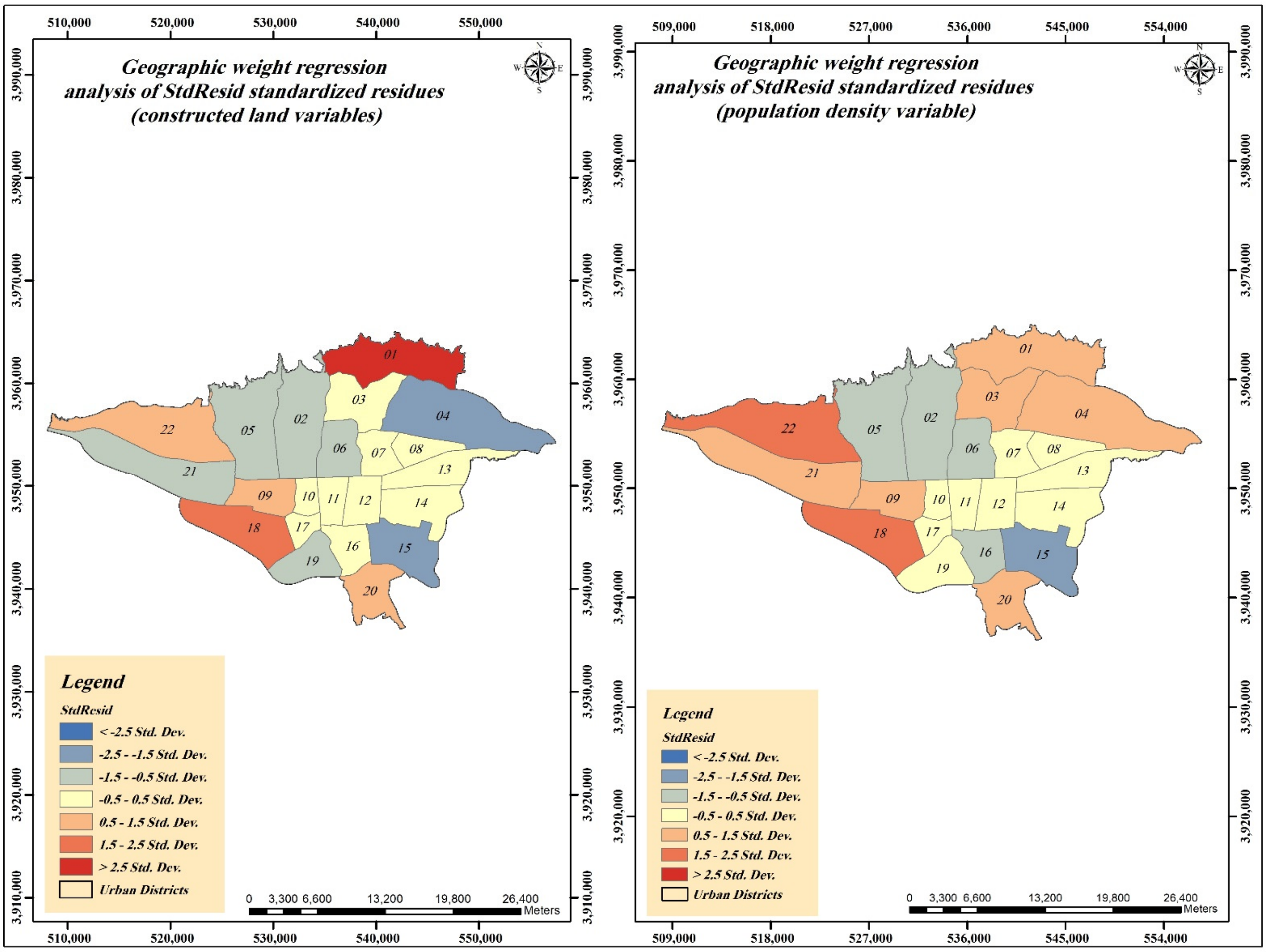

Figure 6. The output layer of GWR analysis of standardised StdResid.

According to the construction land variable, the districts with the highest reduction in vegetation cover also have a standard residual value (StdResid > 3). Districts 1, 20, 18, 9, and 22 experienced the highest reduction in vegetation cover. In other words, construction activities in these districts have expanded into vegetation cover and green spaces. For the population density variable, districts 21, 9, 3, 4, 1, 18, 22 and 20 experienced the most changes over the last 30 years.

Figure 7 shows the estimated coefficients for the independent variables. Spatial analysis of local coefficients indicates that the influence of independent variables in the GWR model varies greatly in different districts of Tehran and has a specific direction.

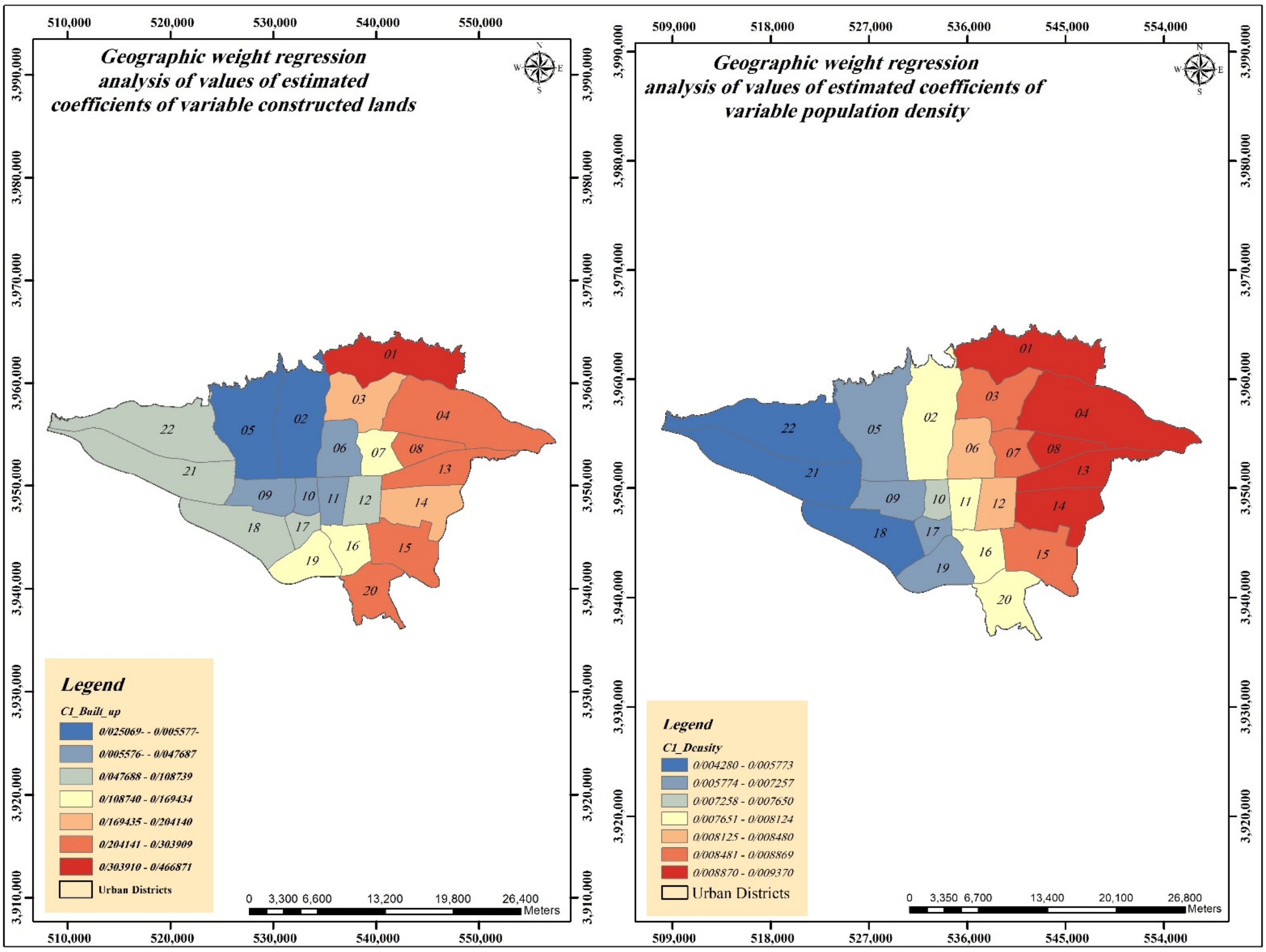

Figure 7. GWR analysis of the values of coefficients estimation of population density variable and constructed lands.

The regression coefficients for the construction land are mainly positive, indicating that the proportion of vegetation cover decreases with the increase in construction activities (mainly land allocated for residential developments). The expansion of construction land in Districts 1, 4, 8, 13, 15 and 20 had a higher impact on the reduction of vegetation cover than in other districts. Similarly, the estimated population density coefficients are positive for all districts of Tehran. Especially, the vegetation cover in districts 1, 8, 14 and 13 decreased with the increase in population density.

4. Discussion

Vegetation cover and green lands are often the first victims of rapid urbanisation all around the world [12,13]. The reduction of green spaces due to the expansion of built-up areas impacts urban ecosystems [14,15], and creates socioenvironmental challenges [16–18]. This is strongly visible in developing countries, where the physical development of cities often leads to the loss of valuable ecological resources, including urban vegetation cover [12–15].

Over the last two decades, many scholars have monitored the impact of urban development on vegetation using different techniques and methods [11,21,23,24]. However, there is little literature focusing on the metropolis of Tehran [71,72]. In this context, this study looked at identifying the vegetation cover changes in the Tehran metropolitan area and the underlying drivers within three main phenomena including, population density, the extent of industrial units, and built-up land development.

The findings indicate that high population density, increased migration, and housing needs have significantly contributed to the destruction of vegetation cover in the Tehran metropolis in recent years. Interestingly, the expansion of industrial units appeared to have the least effect on reducing the vegetation cover.

Five major conclusions can be drawn from this study. First, as the saying goes, the development in the third world is summarised in the capital cities; the same is true in Iran and the city of Tehran. Similar to Deyong et al. (2009) and Shao et al. (2020), this study also found that the urban development pattern in Tehran has been based on the high demand for housing. Lack of proper planning policies, imbalance in the housing supply and demand, lack of urban public services and job opportunities, and disparities in quality of life between Tehran and other cities in Iran are the key drivers behind the unprecedented migration to the Tehran metropolis in recent years [73,74]. In 2006, the population density of Tehran was 829 people per hectare (ha), of which 61 people per ha were added in the recent decade [52]. Population density led to increased housing demand [75], while land scarcity and construction beyond environmental capacity contributed to uneven growth, environmental problems, and a decline in vegetation cover in Tehran [73,76]. More specifically, the development and rapid expansion of the city, driven by the housing demand, have been leading to the destruction of green spaces and vegetation cover.

Second, the reduction in vegetation cover in Tehran over the past 30 years has not been the same in different parts and districts. The extent of construction land development in the peripheral areas of Tehran, including the western, southwestern, northern, north-eastern, and eastern parts, is more significant than in other areas. On the other hand, although the loss of vegetation cover in the central districts is less, the green space area is already low due to industrial and administrative centralisation. The central parts of Tehran have been the economic and commercial nuclei of the city since its formation [77]. Therefore, a high density of industrial and administrative units and low green areas can be seen in the central part of the Tehran metropolis.

Third, the density of industrial units in Tehran is negatively correlated with vegetation cover. Therefore, the common notion that expanding industrial activities negatively impacts green spaces [78,79], does not apply to the city of Tehran.

Fourth, the key factors responsible for the positive correlation between the construction land, population density and reduction of vegetation cover are the intensification of demand for more construction and the inability of urban development plans to achieve balanced development. In Tehran, the growing need for new municipal financial resources often paves the way for green space changes. In Iran, Article 5 and Article 100 commissions (In Iranian cities, assessment and approval of any land use changes are typically done through the Article 5 Commission. The Article 100 Commission in Iran's urban management system deals with the issuance of construction and land division permission. Every citizen must obtain permission from the municipality and the Article 100 Commission before starting construction or land use changes) allow municipalities to change land use by issuing building permits to generate revenue. This mostly happens for conversion of the land use from green space to housing.

Finally, the physical development in the Tehran metropolis is not in harmony with the city's ecological and social issues. Existing research in political ecology highlights that the built environment, spatial distribution and socio-economic activities in cities and metropolitan areas originate from political systems [80]. More specifically, the formation of all urban phenomena is linked to political ideologies and socio-economic conditions [81]. This perspective supports the findings of this study and justifies the relationship between urban construction, population density and vegetation cover reduction in the Tehran metropolis.

5. Conclusions

Vegetation is essential for ecosystem services [1], biosphere action [4] and sustainability [82]. This study analysed the changes in vegetation cover in the Tehran metropolitan area over the past two decades and the underlying drivers.

The results of this study show that the vegetation cover in Tehran has been decreasing over the past 30 years (1990–2020). However, the vegetation loss trends varied across municipal districts. Due to the rapid increase in population density, changes in land use and the growth of construction land, some districts (1, 4, 8, 13, 14, 15, 20 and 22) had a greater decline in vegetation cover than others. In general, the average green space per capita in Iranian cities is between 7–12 square meters (m^2) [83]. According to the 2021 statistics of the Tehran Municipality Information Technology Center, the average green space per capita in Tehran is 8–9 square m^2 per person. This is far below the United Nations (UN) standards of 20–25 square m^2 per person [83].

This study has several research and policy implications. First, it is not only limited to the description and classification of vegetation cover but also attempts to explore the determinants of the process based on objective methods and practical applications, adding a new dimension to the literature on the vegetation cover index. Second, it sheds light on changes in vegetation cover at the metropolis scale and highlights the human and managerial dimensions of the issue. Third, by revealing the influencing factors of vegetation cover reduction, the results can positively change the current situation of vegetation cover in Tehran. Fourth, since other cities in Iran follow Tehran's planning policies, the results can be used to identify factors affecting changes in land use and vegetation cover across the country. Fifth, the findings suggest that housing demand and human activities have played major roles in reducing and destroying the vegetation cover in the Tehran metropolis over the past 30 years. Considering this situation, it is necessary to carefully review and revise the current principles of urban planning and construction rules and apply new rules to limit changes in vegetation and protect urban green spaces in the urban development process. Finally, vegetation cover (both quality and quantity) in urban areas should be considered as part of urban planning to control the impact of urbanisation on vegetation loss and improve urban quality of life.

The results of this study and the variables considered (construction lands, population density and industrial units) can explain and elucidate about 60% of the vegetation cover changes in the Tehran metropolis. The remaining 40% of vegetation cover changes depend on natural and geographical variables. The results of the Geographically Weighted Regression (GWR) model show that 60% of the changes in the vegetation index in Tehran were associated with the growth of construction land area and the increase of population density. The remaining 40% of vegetation changes occurred under the influence of other variables not included in this study. Further research is required to determine the political and economic impacts on the vegetation cover index, as their results can effectively alter the current vegetation degradation patterns in Tehran and other Iranian cities.

Author Contributions: Conceptualization, S.A.Z. and R.T.; Data curation, S.A.Z.; Formal analysis, S.A.Z.; Investigation, S.A.Z.; Methodology, S.A.Z.; Project administration, K.Y.; Resources, K.Y.; Supervision, K.Y.; Visualization, S.A.Z.; Writing—original draft, S.A.Z., K.Y., R.T., F.A. and M.P.; Writing—review and editing, S.A.Z., K.Y., R.T., F.A. and M.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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