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Spatial Modeling of Urban Heat Islands Considering Environmental Factors: A Case Study of Tehran City

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Abstract

In recent decades, Tehran has experienced substantial changes as a result of population expansion, urbanization, and the corresponding development of infrastructure. The aforementioned human activities and modifications in land use patterns at the urban level have resulted in an increase in temperatures and the development of urban heat islands. This matter has emerged as a significant focal point among the scientific community. Given the significance of this subject, the objective of this study is to develop a model for urban heat islands in Tehran, taking into account several environmental parameters. The chosen research methodology is quantitative, encompassing both descriptive and analytical techniques. In this study, we employed satellite images from Landsat 5 and 8, together with TM, OLI, and TIRS sensors provided by the Earth Resources Observation and Science (EROS) Center of the United States Geological Survey. These data sources were utilized to estimate land surface temperatures throughout the summer periods of 2010 and 2021. Clusters of urban heat islands, encompassing both high-risk and low-risk areas, were found by the use of global Moran's I spatial autocorrelation and local Moran's I techniques, namely Hot Spot Analysis and Cluster and Outlier Analysis. Following the verification of geographical patterns in the distribution of urban heat islands, our investigation continued to the identification of clusters characterized by high-risk and low-risk levels. The possible influencing elements, such as elevation, slope, aspect, solar radiation, and road density, were examined in relation to the geographical distribution pattern of these clusters. The findings of our research indicate that within the framework of the Ordinary Least Squares (OLS) regression model, three independent variables, namely elevation, plant cover, and building density, had the most substantial influence. In this study, we examined the many factors that influence land surface temperature and using Geographically Weighted Regression (GWR) to develop a model for predicting urban heat islands in Tehran by the year 2031. In summary, we present suggestions for alleviating the impacts of urban heat islands in Tehran.

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1. Introduction

In light of the continuous process of urbanization occurring globally, there is a growing significance placed on comprehending methods to improve the environmental quality of urban areas. The objective is to create cities that are more appealing and conducive to healthy living, while simultaneously mitigating their negative effects on the environment (Shamsi Khosroshahi et al., 2013).

In recent decades, the actions of humans and their resulting impact on the Earth's climate system have led to the emergence of a significant concern referred to as global warming. This problem has become a topic of extensive deliberation in international arenas. Based on the findings presented in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), it is widely projected by a majority of climate models that the global surface temperature would undergo a rise above 1.5 degrees Celsius by the conclusion of the 21st century, in comparison to the reference period spanning from 1850 to 1900. In a less optimistic scenario, this upward trend might potentially result in a temperature rise of almost 2 degrees. Various factors contribute to the extent of surface temperature increase in urban settings, encompassing weather patterns, geographical latitude, temporal variations, topographical features, atmospheric stability, wind patterns, air pollution levels, population density, artificial heat emissions, building height, street layout, and urban ventilation conditions (Saadat Abadi et al., 2005).

In light of the continuous population growth and unregulated urban sprawl in Tehran, along with the resultant rise in global temperatures attributed to high-density development practices, as well as the deteriorating quality of life experienced by its inhabitants, it is imperative to do this study. This study employs a unique methodology by integrating Remote Sensing (RS) and Geographic Information System (GIS) approaches, hence enhancing its significance in comparison to other research endeavors of a similar nature. The examination of the diverse relevant variables contributing to the phenomenon of urban heat islands is an essential undertaking in the effort to mitigate urban thermal stress and promote the development of sustainable urban design strategies. Cities, being the primary dwelling places of human populations, have to exhibit a conducive atmosphere and meticulously designed infrastructures that effectively address the needs and requirements of their residents. Through the implementation of this research, it becomes apparent which variables have a substantial impact on the spatial distribution of urban heat islands in Tehran.

The expansion and development of big cities have led to the emergence of urban heat islands, which are widely recognized as significant effects. The impacts resulting from the development of urban heat islands can have a significant and crucial influence on air quality and, subsequently, the well-being of the general population. The current situation is occurring amidst a global context characterized by an unparalleled surge in industrialization and uncontrolled urbanization. The rise of urbanization has resulted in the conversion of extensive agricultural fields and woods into residential and industrial locations, which are widely acknowledged as hubs of human productivity, habitation, and connectivity to societal advancements. The process of industrial expansion, along with the concurrent rise in urbanization, has resulted in the widespread degradation of agricultural areas, loss of vegetative cover, and a substantial diversion of water supplies for urban and industrial use. The replacement of natural landscapes by artificial ones results in alterations to land surface materials, which subsequently cause diverse adjustments in surface reflectance, heat retention, and heat transport. These variations have significant implications for local climatic conditions. inside the field of urban studies, a multitude of research endeavors have been conducted, encompassing the analysis of distinct urban phenomena and the quantification of diverse characteristics inside the urban environment.

Broadly speaking, research undertaken in the realm of urban heat islands may be categorized into two major divisions, distinguished by the data utilized and the technique employed. The initial set of investigations use data obtained from meteorological stations. These studies aim to examine the temperature variation between selected places in developed metropolitan regions and less-developed urban or rural areas. The researchers pick two or more temperature measurement stations as representations of these areas and analyze the temperature differences. Additionally, they provide their insights on the characteristics and structure of the heat island phenomenon in the region. The urban heat island phenomenon in Rasht was investigated by analyzing daily data collected from 14 synoptic stations situated inside the city and its environs. The findings indicate that in conditions of low temperature, there exists a temperature disparity ranging from 5.6 to 6.5 degrees Celsius between the core of the urban heat island and its adjacent environs. The variation in this disparity ranges from 3.6 to 6.5 degrees Celsius when considering maximum temperature conditions. The subsequent set of investigations has been carried out with thermal imaging and remote sensing technologies. The majority of these research have primarily concentrated on examining the correlation between alterations in land cover and the spatiotemporal patterns of land surface temperature. The researchers utilized TM sensor data to investigate the phenomenon of urban heat islands and subsequently produced maps illustrating the dispersion of heat and pollutants inside the city of Tehran.

In their study, Shokouh et al. (2009) sought to analyze the urban heat islands in Tehran by utilizing satellite data. The primary objective was to investigate the influence of land cover on surface temperatures inside the city. The researchers conducted a study in Tehran to categorize the land cover in metropolitan areas. They employed sub-pixel classification techniques and analyzed biophysical parameters to extract information on soil fraction, plant cover, and impervious surfaces. This was achieved by utilizing ETM+ data. The findings of their study demonstrated that impermeable surfaces have a warming impact due to their capacity to absorb and retain solar radiation, whereas plant cover has a cooling effect by promoting thermal equilibrium through evapotranspiration and the creation of shaded areas.

A comprehensive examination of prior research conducted in Tehran indicates that the majority of studies have predominantly concentrated on the determination of Tehran's urban heat island's geographic magnitude, generally employing a solitary thermal picture. Several research were conducted with the objective of developing suitable methods for extracting surface temperature in Tehran. Additionally, additional studies investigated the impact of land use patterns on the thermal pattern of Tehran. In addition, Sadeghiania et al. (2012) conducted a study to investigate the correlation between Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI) in the urban area of Tehran, utilizing Landsat images.

This study aimed to estimate surface temperatures by utilizing thermal imaging obtained from satellite sensors including Landsat 8 and 5, OLI, TIRS, and TM. The objective of this study was to identify clusters of urban heat islands that pose high and low risks. To do this, we employed global and local Moran's tests. Additionally, we conducted an analysis using ordinary least squares (OLS) regression to examine the factors that influence the occurrence of urban heat islands. Finally, our objective was to forecast the future state of Tehran's urban heat island by employing GWR regression methodology.

2. Study Area

The research is conducted in Tehran, the capital of the Islamic Republic of Iran. Tehran is situated between 51 degrees 17 minutes to 51 degrees 33 minutes east longitude and 35 degrees 36 minutes to 35 degrees 46 minutes north latitude. The city's elevation ranges from approximately 1,050 meters in the south to 1,800 meters in the north and 1,200 meters in the central region (Mahmoudian, 2008, p. 27). The research area's geographical location is illustrated in Figure 1.

Tehran is located on the southern foothills of the Alborz mountain range and the northern edges of the central Iranian desert, lying within a predominantly flat plain. The urban area has a landmass of roughly 730 square kilometers. The thermal ecology of the region has been greatly affected by its fast-urban expansion and inadequate planning (Sadeghiania, 2012, p. 3).

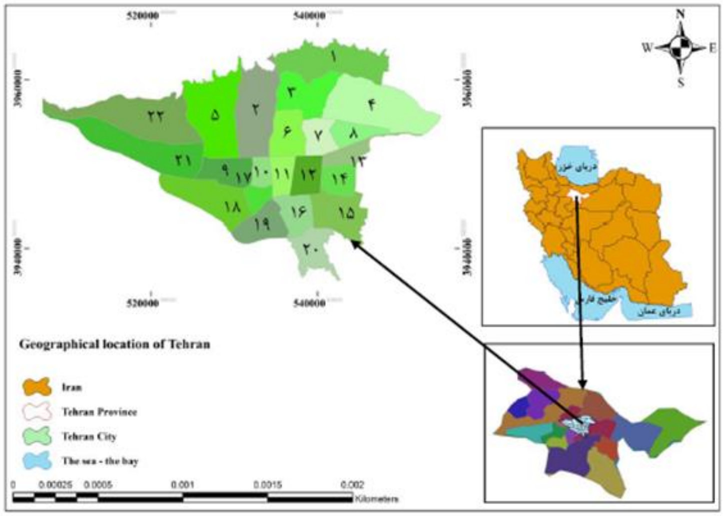

Figure 1. Geographic Location Map - Tehran City

3. Data Collection and Methodology

This study employed satellite imagery from Landsat 5 and Landsat 8 to estimate land surface temperatures. Once the ideal image was chosen, the region of interest (namely, Tehran city) was separated and subsequently stored using the process of band stacking. The present study originally examined relevant factors that have the ability to effect urban heat islands. The study analyzed the correlation, nature, and magnitude of these associations. The geographical correlations between these variables and the urban heat island variable were modeled, taking into account their relevance.

The software tools employed in this study encompass image processing software such as TERRSET and Global Mapper, with the Geographic Information System (GIS) program, ARC GIS. In order to analyze the spatial and temporal variations in temperature, cloud-free and clear photos of Tehran's metropolitan area on June 18, 2021 were acquired from the USGS Earth Explorer website. The images were specifically retrieved in bands 10 and 4, route 164, and row 35. Furthermore, in the context of spatial modeling and prediction, it was necessary to utilize photographs specifically from the year 2010. In order to achieve this objective, imagery captured on June 18, 2010, was acquired from Landsat 5 through the official website of the United States Geological Survey (USGS). The data for the research region was acquired from the Giovanni website (https://giovanni.gsfc.nasa.gov), utilizing the Atmospheric Infrared Sounder (AIRS) instrument. The Digital Elevation Model (DEM) data were obtained from the Alos Palsar sensor, which may be accessed at the following website: https://search.asf.alaska.edu. The road network density statistics were acquired from the website https://www.openstreetmap.org.

The integration of these information and software tools enabled a thorough examination of urban heat islands and the underlying variables impacting them within the Tehran city region.

Table 1. Information of Acquired Images from Landsat Satellite

Mechanical separation	Sensor	Path/row	Time	Cloud cover %	Solar date	AD date	Satellite	Row
30	TM	164/35	13:00	0	28/03/1389	18/06/2010	Landsat5	1
30	OLI/TIRS	164/35	13:00	0	28/03/1400	18/06/2021	LLandsat8	2

4. Findings of the Study

The computation of land surface temperature was conducted utilizing the appropriate data, as indicated in Figure 2. In order to evaluate the precision and credibility of the research, an examination was performed on the resultant maps depicting land surface temperature within the designated study region. For the aim of this study, five locations in Tehran were chosen to represent various land uses, including green spaces, built-up surface cover, bare soil, and water bodies. The sites chosen for study encompassed Chitgar Lake, Kuh-e Siah Park, Mehrabad Airport, the vicinity around the Caspian Sea, and Valiasr Park.

Persian Lake Gulf and Koohsar Park are two geographical areas characterized by somewhat lower temperatures. Through the analysis of temperature maps at certain locations inside Koohsar Park, namely points 2-2 and 2-3, it becomes evident that the inclusion of green spaces within the park has resulted in a notable reduction in surface temperatures. The incorporation of evapotranspiration mechanisms originating from vegetative cover has resulted in a reduction in surface temperature, hence alleviating the urban heat island phenomenon. The presence of vegetation mitigates soil evaporation and addresses environmental aridity through its shading properties and ability to decrease wind speed. Moreover, it is worth noting that water features, such as those present in Persian Lake Gulf, exhibit a diminished capacity for heat absorption in comparison to the arid terrain around them. Consequently, this disparity contributes to noticeable mitigations in the magnitude of urban heat islands.

Three other sites, situated at coordinates 2-4, 2-5, and 2-6, correspond to desolate areas surrounding the Caspian Sea, Mehrabad Airport, and Valiasr Park, respectively, where localized regions of elevated temperatures are observable.

The urban heat island effect exerts a significant influence on the Mehrabad Airport vicinity. The primary factors contributing to this issue are the arid landscapes encompassing Mehrabad International Airport, the congestion prevalent in the neighboring streets, and the substantial presence of both public and private automobiles.

The urban heat island effect is particularly evident in the areas surrounding Persian Lake Gulf and Valiasr Park. This phenomenon can be mostly attributed to the vast expanses of arid terrain present in these regions.

The presence of impermeable hard surfaces, such as stone pavements, asphalt, and barren fields, exacerbates the flow of heat and moisture. The research findings, which are substantiated by the output temperature maps, clearly indicate that the decrease in urban green areas plays a pivotal role in the development of urban heat islands. These regions, which are distinguished by a large number of impermeable surfaces, infertile soils, and a scarcity of vegetation, result in considerably elevated surface temperatures during the day and the formation of urban heat islands.

A spatial auto-correlation analysis (Moran's I) was undertaken to characterize the neighborhoods in Tehran based on the presence of high-risk and low-risk clusters of urban heat islands. The conducted study was crucial in validating the hypothesis that there are geographical clusters of land surface temperature (LST) patterns present in communities inside Tehran. The geographical distribution seen in Figure 3 exhibits notable clusters, as evidenced by a Moran's Index value of 0.215, which indicates the presence of positive spatial autocorrelation. The statistical importance of these clustering patterns is further substantiated by the P-value and Z-score.

The P-value is approaching 0, indicating a high level of statistical significance. Additionally, the Z-Score, calculated to be 8.91, indicates that the geographical distribution of Land Surface Temperature (LST) demonstrates a clearly defined clustered pattern. The present research presents compelling evidence on the existence of clusters of urban heat islands inside the districts of Tehran.

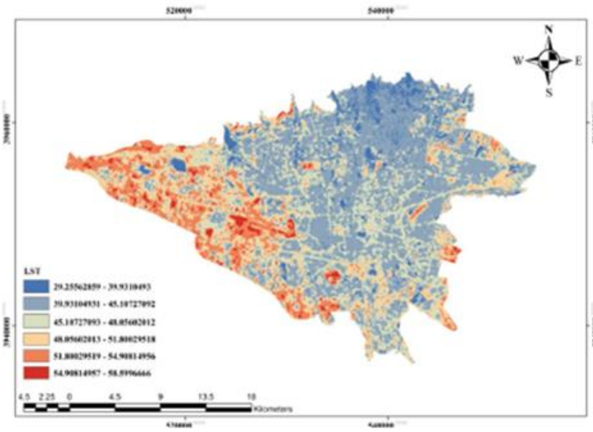

Figure 2.1 Ground Level Map - Tehran City

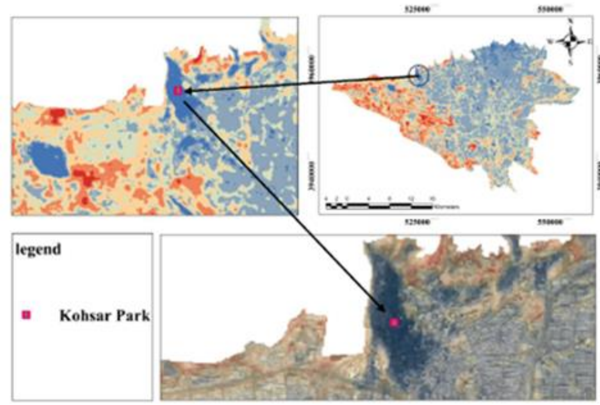

Figure 2.2 Ground Level Map - Tehran City- Kuhsar Park

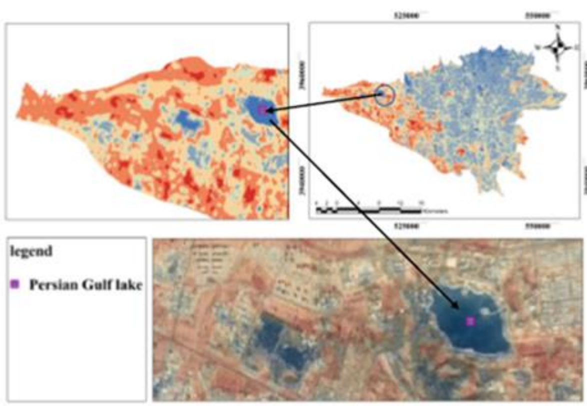

Figure 2.3 Ground Level Map - TehranCityPersianLakeGulf

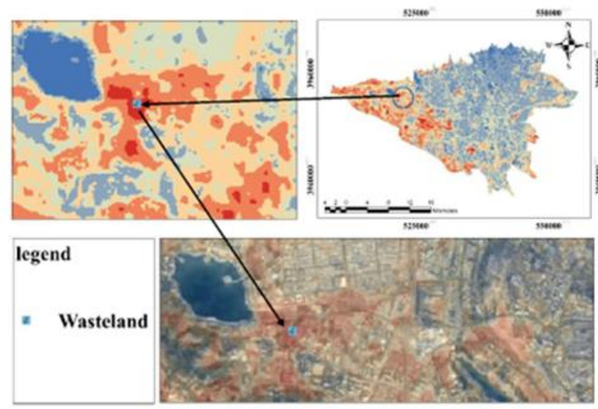

Figure 2.4 Ground Level Map - Tehran City- Barren Lands Around the Lake

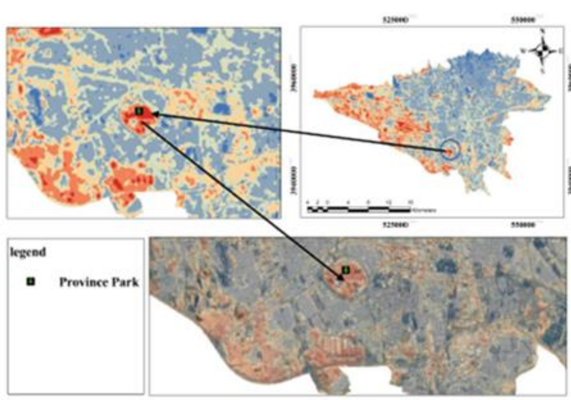

Figure 2.5 Ground Level Map - Tehran City-Velayat Park

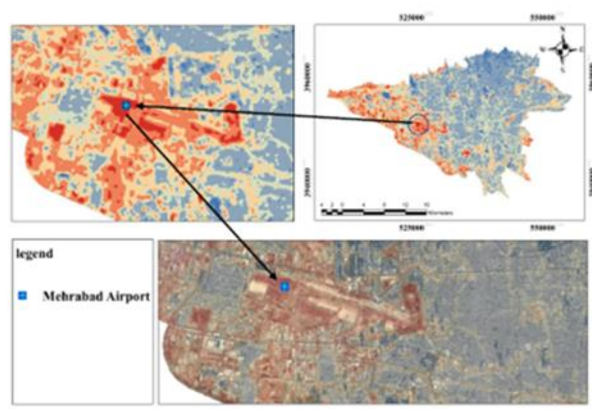

Figure 2.6 Ground Level Map - Tehran City- Mehrabad Airport

Figure 2.

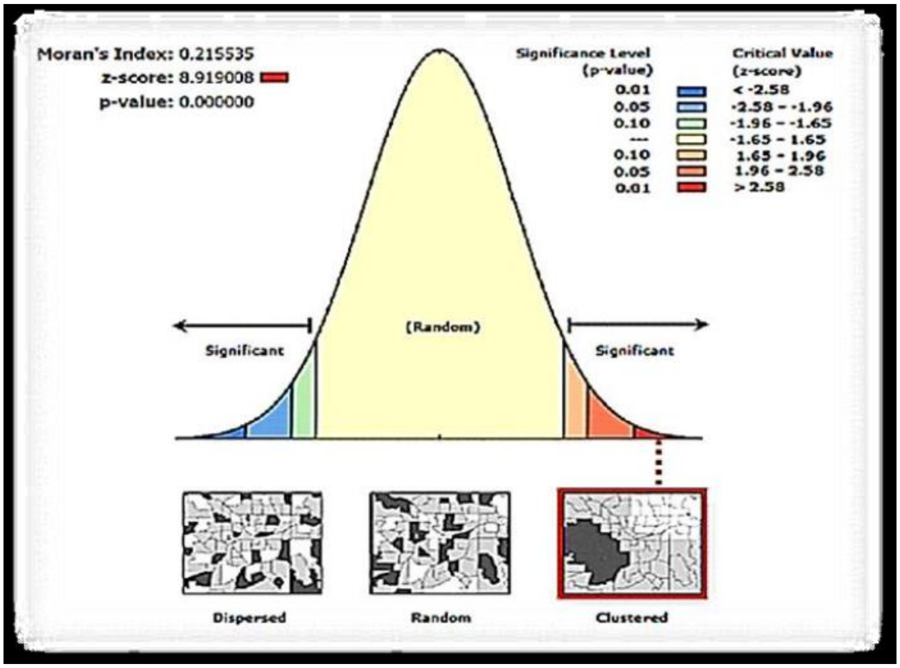

Figure 3. Moran's Spatial Autocorrelation Analysis

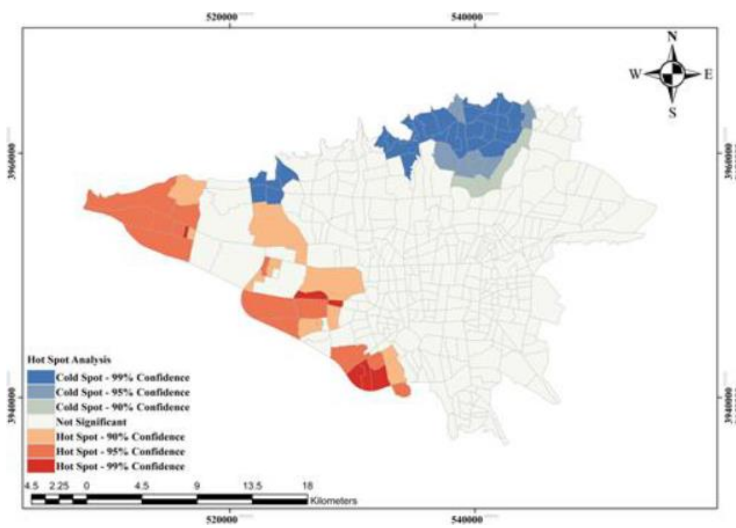

Figure 4. Map of High-Risk and Low-Risk Clusters in Tehran City

Following the confirmation of clustering patterns in the distribution of land surface temperature (LST) in Tehran, the use of local Moran's analysis was utilized to detect clusters with high-risk and low-risk characteristics. Figure 4 displays three distinct groups of low-risk clusters or cold patches, denoted by the color blue, each corresponding to confidence levels of 90%, 95%, and 99%. Furthermore, the visualization displays three distinct classifications of high-risk clusters or hot spots, each associated with confidence levels of 90%, 95%, and 99%, respectively, represented by the color red. A category without a confidence level is shown in gray with little dots.

The presence of low-risk clusters of land surface temperature, with a confidence level over 95%, may be observed at the northern and northwestern boundaries of the designated research region, as depicted by the blue coloration. Nevertheless, there are dispersed high-risk clusters of land surface temperature in the western and southwestern areas, with a confidence level over 95%, as indicated by the color red. The remaining regions lack statistical significance and hence do not yield valid findings.

To achieve a more comprehensive characterization of high-risk and low-risk clusters of land surface temperature, the study employed an analytical approach that involved the examination of both clustered and non-clustered areas, which were delineated based on the districts of Tehran. Figure 5 displays the High-High Cluster and Low-Low Cluster, which correspond to clusters with high and low levels of risk, respectively. The distribution of these clusters closely aligns with the findings derived from the hot and cold spot study. The data indicates that regions with lower risk of land surface temperature are located in the northern and northwestern portions of the research area, as seen by the blue coloration. Nevertheless, there is a notable concentration of high-risk clusters in the western and southwestern areas, as shown by the color red. The classifications of High-Low Outlier and Low-High Outlier pertain to regions that are not grouped. The initial classification, referred to as "High-Low Outlier," represents geographical locations characterized by a pronounced likelihood of experiencing elevated land surface temperatures, juxtaposed with surrounding regions exhibiting comparatively lower temperatures. This research encompassed five distinct locations, each exhibiting specific features. The second group, referred to as "Low-High Outlier," depicts places characterized by a relatively low land surface temperature juxtaposed with surrounding areas exhibiting greater temperatures. It is probable that these regions will see a rise in land surface temperature as a result of their close proximity to places characterized by high temperatures. Hence, the present analysis identifies high-risk urban heat island clusters located in the western and southwestern regions of Tehran.

Figure 6 displays a zoning map that categorizes different places according to their land surface temperature. The analysis of land surface temperature distribution indicated that the regions with the greatest levels of temperature are located in the western and southwestern areas of Tehran, predominantly in the periphery of the designated study zone.

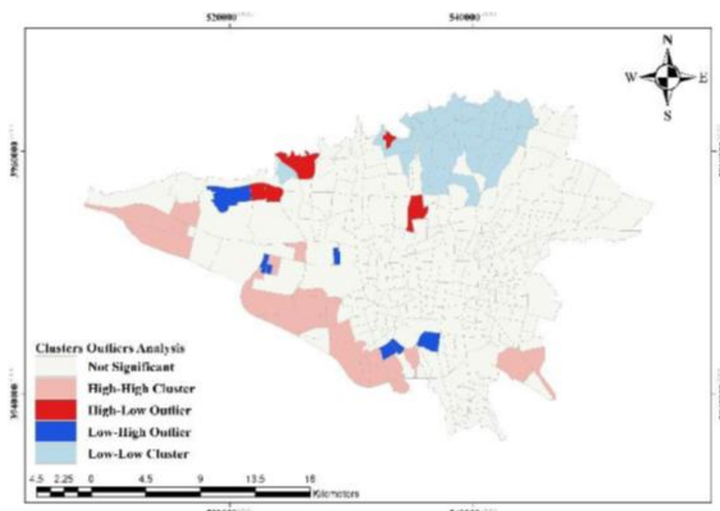

Figure 5. Cluster and Non-cluster Analysis Map - Tehran City

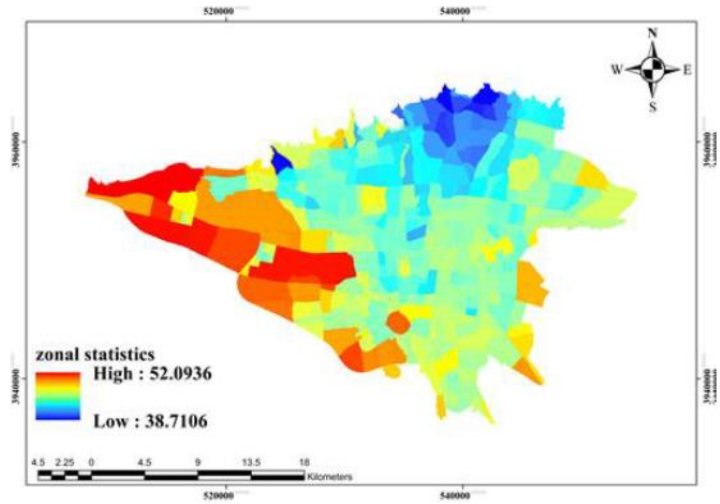

Figure 6. Regional Zoning of Land Surface Temperature - Tehran City

5. Data Analysis and Results

Through the utilization of Ordinary Least Squares (OLS) regression analysis, this study explored many potential factors that may influence the creation of the urban heat island (UHI) in Tehran, while considering the spatial distribution patterns of high-risk and low-risk clusters. The elements encompassed in this study comprise elevation, NDVI (Normalized Difference Vegetation Index), NDBI (Normalized Difference Built-up Index), solar radiation levels, slope, aspect, and 2CO (Carbon Monoxide concentration).

A Digital Elevation Model (DEM) is a representation of the Earth's surface in digital form, typically in the form of a grid or raster dataset. It provides information on the elevation or height of the terrain Elevation has a vital impact in UHI creation. Low-lying locations and valleys exhibit a greater capacity for heat absorption during diurnal periods, while concurrently experiencing less susceptibility to wind patterns. Consequently, these geographical features manifest enhanced temperatures in contrast to elevated places. The Digital Elevation Model (DEM) is a crucial spatial dataset that finds use in a wide range of fields, such as hydrological research, topographic mapping, picture geometric correction, extraction of land surface parameters, natural disaster management, and others (Alidoust and Dadrasjavan, 2013, p. 75). The DEM of Tehran City is seen in Figure 7.

The Influence of Elevation on Urban Heat Islands: The ordinary least squares (OLS) regression analysis revealed a robust and inverse relationship between elevation and urban heat island (UHI) generation in Tehran. Put simply, a rise in altitude is associated with a decline in Urban Heat Island (UHI) intensity, whereas a drop in altitude is linked to an increase in UHI intensity.

In conclusion, the findings of this study demonstrate a strong negative correlation between elevation and the occurrence of urban heat islands in the city of Tehran. The severity of the urban heat island (UHI) phenomenon decreases as elevation increases, aligning with the premise that higher altitudes often exhibit lower temperatures as a result of increased wind exposure and decreased heat absorption. The aforementioned results emphasize the significance of incorporating topographical characteristics into urban design and policies aimed at mitigating the urban heat island (UHI) effect, especially in areas with diverse elevations such as Tehran.

Table 2. OLS Regression - Independent Variable Results - Digital Elevation Model - Tehran City

Summary of OLS Results - Model Variables							
Variable	**Coefficient [a]**	**StdError**	**t-Statistic**	**Probability [b]**	**Robust_SE**	**Robust_t**	**Robust_Pr [b]**
Height	-0.01774	0.006549	2.708595	0.013521*	0.005258	-3.373707	0.003019*

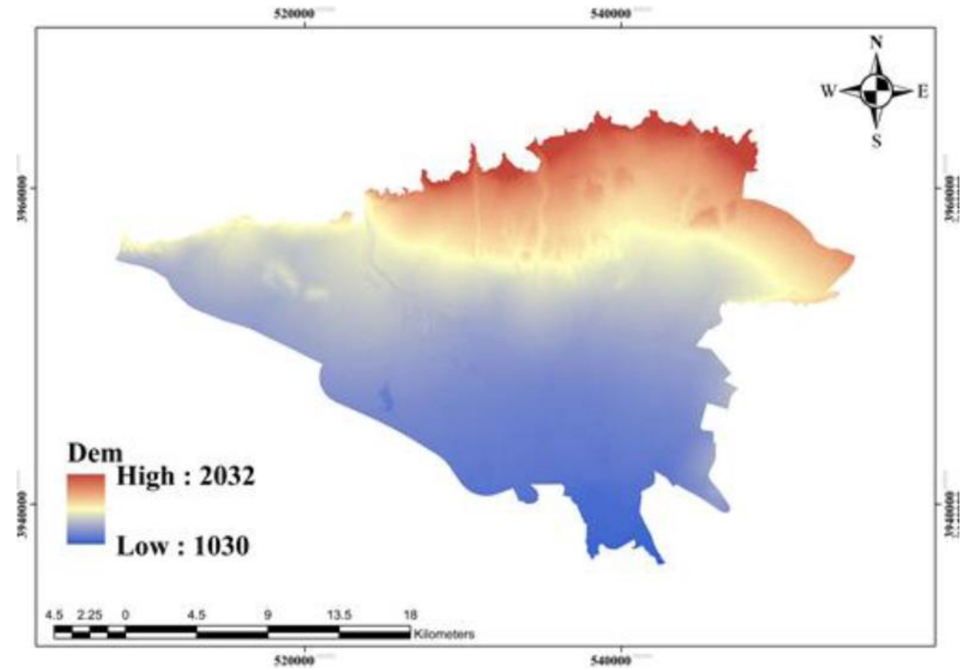

Figure 7. Digital Height Model- Tehran City

The monitoring of changes in plant cover is of paramount importance in the fields of urban planning and environmental management. One widely used method for this purpose is the Normalized Difference plant Index (NDVI). The phenomenon of urban heat islands is shaped by the escalation of impermeable surfaces and the reduction of green spaces. Locations that possess plant cover often exhibit cooler temperatures in comparison to other areas. The phenomenon of heat islands in this location can be attributed to the loss or reduction of plant cover, as well as the existence of hard and impermeable surfaces.

The vegetation cover in Tehran City is seen in Figure 8. The findings derived from the examination of plant cover in Tehran City, as presented in Table 3, demonstrate a noteworthy correlation between this factor and the urban heat island phenomenon. The observed association between plant cover and the prevention of heat island development is robust and exhibits a negative correlation. Specifically, areas with greater levels of vegetation cover demonstrate a more pronounced effect in mitigating the creation of heat islands. In contrast, a decrease in plant cover that is dispersed over an area contributes to the development of urban heat islands.

Table 3. OLS Regression - Independent Variable: Vegetation Cover - Tehran City

Summary of OLS Results - Model Variables							
Variable	**Coefficient [a]**	**StdError**	**t-Statistic**	**Probability [b]**	**Robust_SE**	**Robust_t**	**Robust_Pr [b]**
NDVI	-29.516738	4.360035	-6.769839	0.000001*	4.727856	-6.243155	0.000004*

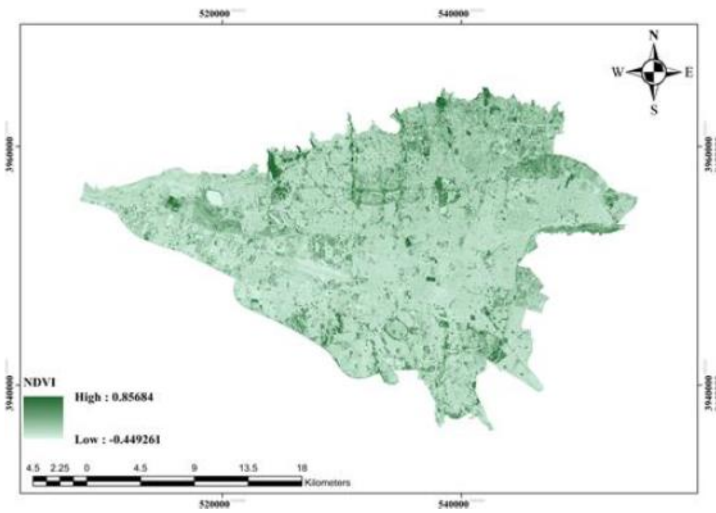

Figure 8. Vegetation Cover - Tehran City

The concept of the Normalized Difference is a widely used technique in remote sensing and image analysis. The Built-Up Index (NDBI) is a commonly employed metric for evaluating urban characteristics and distinguishing residential regions from non-residential regions. Tehran, the capital city of Iran, exhibits a variety of land uses, encompassing residential, industrial, commercial, and military sectors. The various land uses within metropolitan areas might exhibit unique temperature patterns, which in turn can influence surface temperatures. Figure 9 depicts the urbanized regions inside the city of Tehran.

According to the findings shown in Table 4, the examination of built-up areas in Tehran reveals a robust association between this factor and the urban heat island phenomenon inside the city. The presence of built-up regions is a significant contributing element to the phenomenon known as urban heat islands. The observed connection exhibits a positive and strong relationship, indicating that an increase in the density of built-up structures is associated with a corresponding rise in the intensity of urban heat islands, and conversely, a decrease in density is associated with a decrease in intensity.

Table 4. OLS Regression Results - Independent Variable: Built-Up Areas - Tehran City

Summary of OLS Results - Model Variables							
Variable	**Coefficient [a]**	**StdError**	**t-Statistic**	**Probability [b]**	**Robust_SE**	**Robust_t**	**Robust_Pr [b]**
NDBI	36.984189	12.710537	2.909727	0.008664*	15.427939	2.397222	0.026402*

The level of solar radiation exhibits variability across several temporal and spatial dimensions. those closer to the equator have more solar radiation influx in comparison to those farther away from the equator, resulting in a notable impact on heat creation. The manner in which objects located on the Earth's surface absorb and reflect solar radiation varies. Metal structures, such as buildings, have been shown to possess a greater capacity for solar energy absorption compared to concrete structures. This disparity in energy absorption leads to elevated temperatures within metal structures, thereby exerting an influence on the immediate surroundings.

The sun radiation in Tehran is seen in Figure 10. Nevertheless, the findings depicted in Table 5 indicate that there is an absence of a statistically significant correlation between the independent variable of solar radiation and the dependent variable, namely Land Surface Temperature (LST), inside the urban area of Tehran.

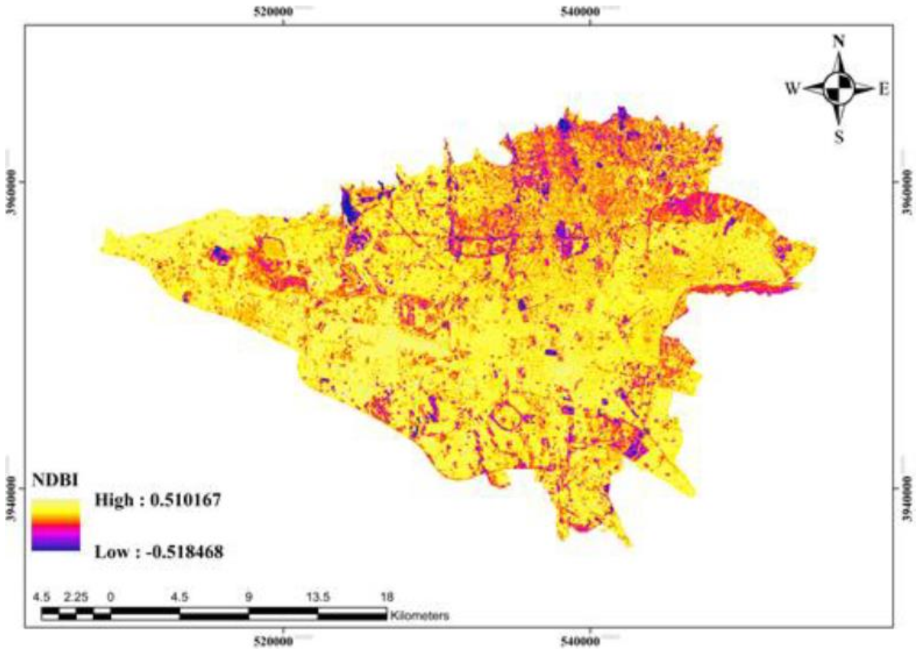

Figure 9. Built-Up Areas - Tehran City

Table 5. Regression. – OLS. Results of The Independent Variable - Solar Radiation - Tehran City

Summary of OLS Results - Model Variables							
Variable	**Coefficient [a]**	**StdError**	**t-Statistic**	**Probability [b]**	**Robust_SE**	**Robust_t**	**Robust_Pr [b]**
solar radiation	0.000042	0.000051	0.823959	0.419682	0.000046	0.914638	0.371279

The amount of solar radiation received varies depending on the slope and aspect of a given area. Slopes oriented towards the north, northeast, and east see reduced solar exposure, leading to decreased temperatures. Slopes oriented towards the south and southwest see a greater influx of solar radiation, resulting in elevated temperatures. The influence of topographic characteristics on land surface temperature (LST) is evident. However, the dynamic nature of LST and the consistent topography circumstances across time necessitate a more comprehensive evaluation beyond only examining topographic conditions.

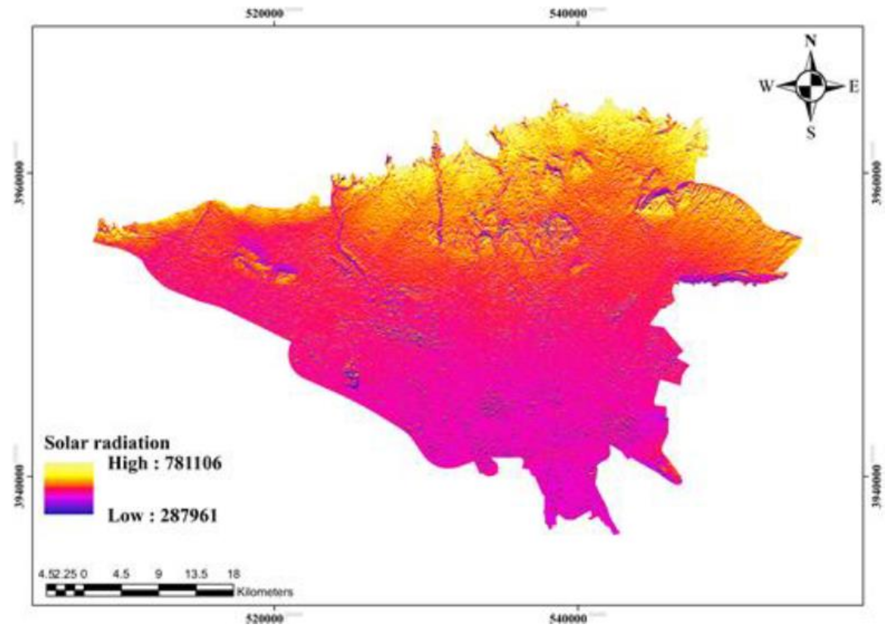

Figure 10. Solar Radiation Map - Tehran City

The following is a summary of the ordinary least squares (OLS) regression findings for the variables:

According to the findings presented in Tables 6 and 7, the analysis conducted on slope and aspect in Tehran indicates that there is no statistically significant link between the independent variables of slope and aspect and the dependent variable, Land Surface Temperature (LST).

Table 6. Regression – OLS Results of The Independent Variable "Slope" In Tehran

Summary of OLS Results - Model Variables							
Variable	**Coefficient [a]**	**StdError**	**t-Statistic**	**Probability [b]**	**Robust_SE**	**Robust_t**	**Robust_Pr [b]**
slope	**0.128969**	**0.270668**	**0.476485**	**0.638893**	**0.186605**	**0.691133**	**0.497426**

Table 7. Regression. – OLS. Results of The Independent Variable "Slope Aspect" In Tehran

Summary of OLS Results - Model Variables							
Variable	**Coefficient [a]**	**StdError**	**t-Statistic**	**Probability [b]**	**Robust_SE**	**Robust_t**	**Robust_Pr [b]**
Slope aspect	**0.000381**	**0.010821**	**0.035199**	**0.97227**	**0.010143**	**0.037554**	**0.970415**

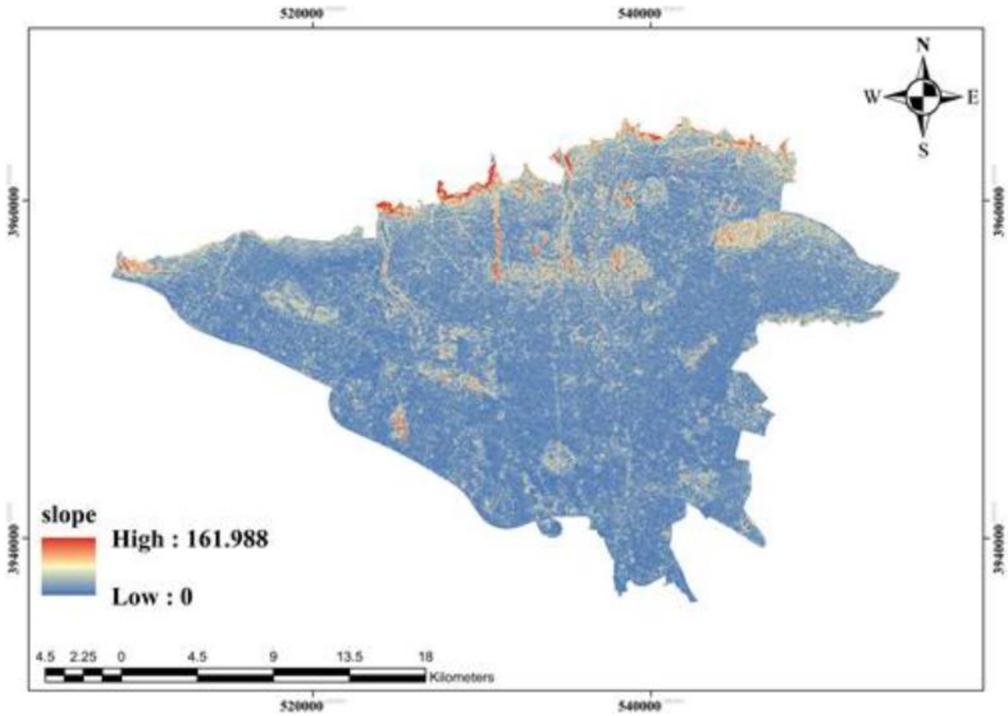

Figure 11. Aspect Map - Tehran City

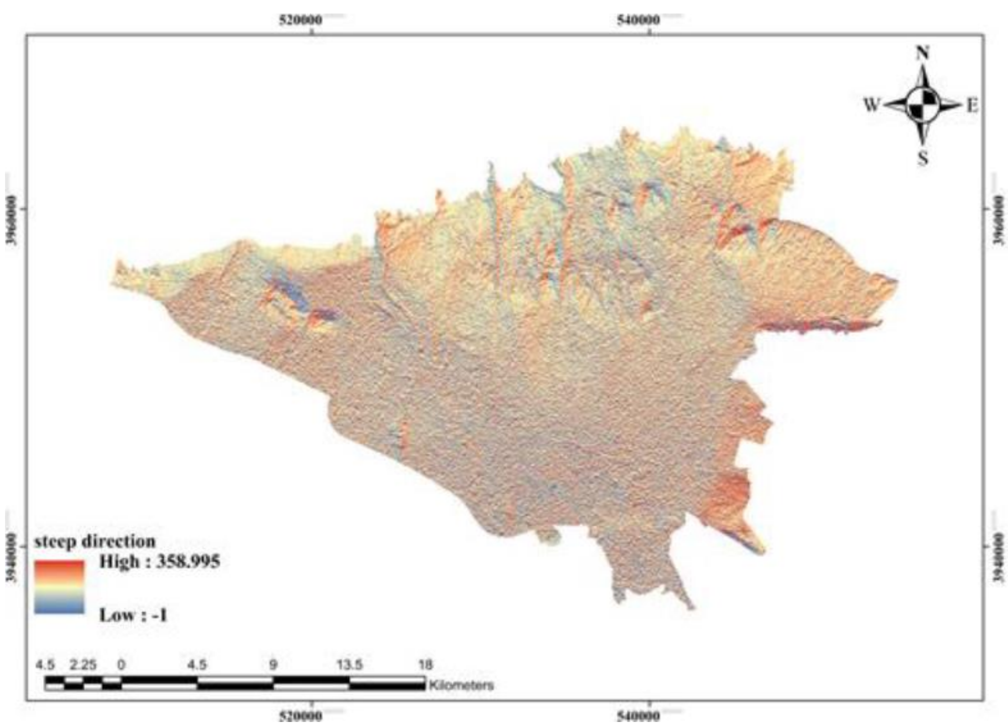

Figure 12. Slope Aspect- Tehran City

This section presents a summary of the results pertaining to the independent variable of road network density in Tehran City. Communication networks, commonly referred to as roads, constitute around 33% of the whole metropolitan land area and serve as the fundamental infrastructure of a city. Roads have a significant role in shaping the layout, urban geometry, and overall growth of a city, including several aspects associated to urbanization. The significance of effectively structuring the network of tunnels and roadways may be seen from two distinct perspectives. There are two primary impacts of this phenomenon. Firstly, it exerts a direct influence on the broader urban framework. Secondly, it plays a crucial role in shaping the availability and accessibility of various services. The correlation between urban growth and the necessity for a rise in both the quantity and proportion of road networks is apparent, mostly due to the escalating levels of traffic congestion.

Figure 13 illustrates the road network density of Tehran City. Based on the findings shown in Table 8, it can be concluded that there is no statistically significant association between the independent variable, road network density, and the dependent variable, land surface temperature (LST).

Table 7. Regression. – OLS. Results of Independent Variable – Road Network Density – Tehran City

Summary of OLS Results - Model Variables							
Variable	**Coefficient [a]**	**StdError**	**t-Statistic**	**Probability [b]**	**Robust_SE**	**Robust_t**	**Robust_Pr [b]**
Road Network Density	-966.158978	554.24191	-1.743208	0.09665	570.196381	-1.694432	0.105698

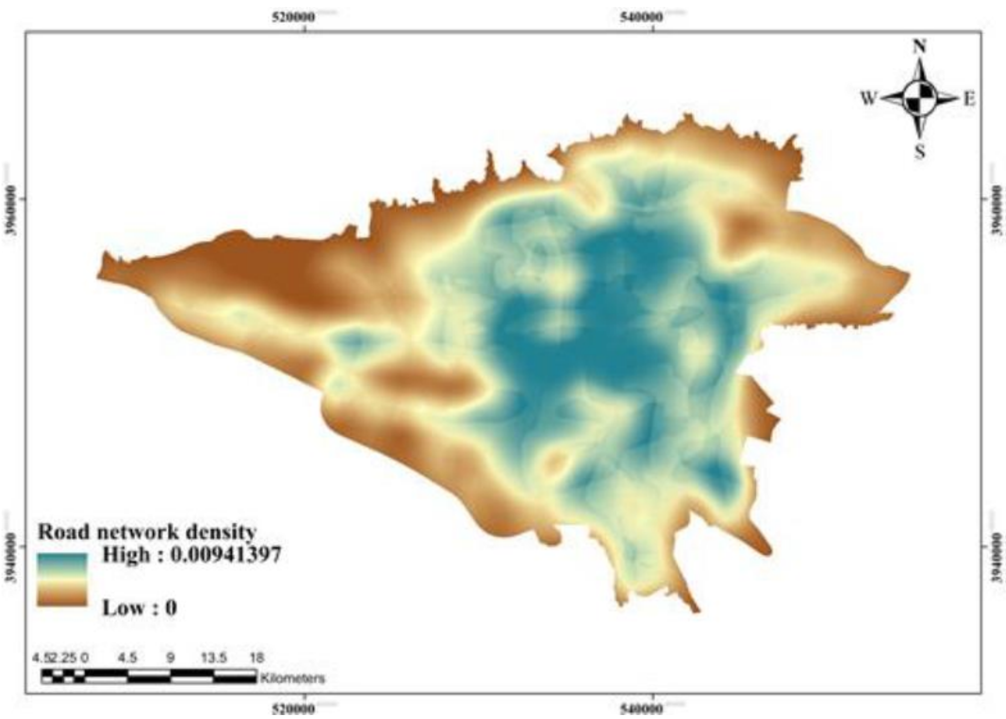

Figure 13. Road Network Density Map - Tehran City

The atmospheric concentration of carbon dioxide (CO2) is on the rise, making it a significant greenhouse gas and a crucial element in the carbon cycle. The task of mapping and simulating alterations in carbon storage and sequestration within ecosystems poses significant challenges. Spatial inputs and information pertaining to the carbon cycle exhibit variability across different geographical locations. Certain fields of study provide abundant and reliable data that can be subjected to thorough analysis, enabling researchers to delve into intricate details. Conversely, there are other domains where the availability of essential information is insufficient to facilitate the modeling of spatial and performance variations. The generation of carbon dioxide from anthropogenic sources may be classified into two main categories: mobile sources and permanent sources. Mobile sources encompass both land and air transportation, whereas fixed sources, which are the primary contributors of carbon dioxide emissions, consist of power plants, cement and steel companies, refineries, and ethanol producing facilities.

Figure 14 depicts the spatial distribution of carbon dioxide (CO2) inside the urban area of Tehran. Based on the data acquired from the Giovanni website, the most recent accessible information pertaining to the research region in 2017 reveals that the analysis findings indicate a lack of statistical significance in the association between the independent variable (CO2) and the dependent variable (LST).

Table 9. Regression. – OLS. Results of Independent Variable - Carbon Dioxide (CO2) - Tehran City

Summary of OLS Results - Model Variables							
Variable	**Coefficient [a]**	**StdError**	**t-Statistic**	**Probability [b]**	**Robust_SE**	**Robust_t**	**Robust_Pr [b]**
CO2	-50.231274	23.10112	-2.174409	0.041849*	27.203357	-1.84651	0.079668

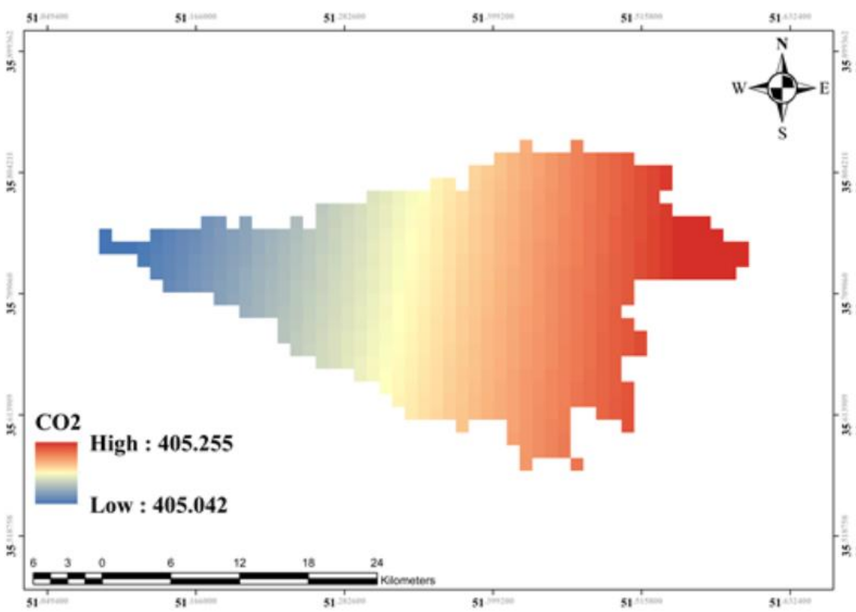

Figure 14. Carbon Dioxide Map - Tehran City

The study investigated the correlation between three variables, namely vegetation covering (NDVI), height, and building density (NDBI), among different groups categorized by the variable LST (Land Surface Temperature), as presented in Table 10. After including these factors into the Ordinary Least Squares (OLS) regression model, the findings revealed that the three independent variables, namely NDVI, height, and NDBI, exert a statistically significant impact on Land Surface Temperature (LST) in Tehran City.

Based on the observations, it can be noted that there exists a significant negative connection between the height variable and LST. The correlation coefficient of -0.015461 indicates that as the height increases, the LST tends to decrease. Nevertheless, the strength of this association is somewhat less pronounced in respect to the other two factors. Moreover, it has been shown that the reduction in vegetation covering and the expansion of built-up areas are associated with an increase in Land Surface Temperature (LST), thus suggesting that these variables have a role in the phenomenon known as the Urban Heat Island (UHI) effect. The NDBI variable has a positive correlation with LST, indicating that higher building density is associated with a greater urban heat island (UHI) impact.

In contrast, there is an inverse link between vegetation coverage and height variables and land surface temperature (LST), with the coefficient of vegetation coverage (NDVI) being higher in magnitude compared to the other variables. Therefore, it may be inferred that the NDVI variable has a more significant influence in comparison to other factors. The three variables had a statistically significant correlation with the LST variable.

Table 10. Regression. – OLS. Variables Influencing the Urban Heat Island Effect in Tehran City

Summary of OLS Results - Model Variables								
Variable	**Coefficient [a]**	**Std Error**	**t-Statistic**	**Probability [b]**	**Robust SE**	**Robust t**	**Robust Pr [b]**	**VIF [c]**
NDVI	-18.412819	3.864625	-4.764451	0.000155*	3.339375	-5.513851	0.000031*	1.586202
Height	- 0.015461	0.004031	3.835312	0.001213*	0.003665	4.21907	0.000516*	1.530277
NDBI	13.619953	6.470385	2.104968	0.049603*	5.916095	2.302186	0.033477*	1.209903

Following the identification of the relevant variables on Land Surface Temperature (LST), the research direction changed towards the development of models to forecast LST specifically for the year 2031. After conducting many tests and comparisons to identify relevant factors in ordinary least squares (OLS) regression, a group analysis was performed to examine the associations between three variables: vegetation covering, height, and building density, with the land surface temperature (LST) variable. In conclusion, a notable association between the three factors and LST has been shown.

In order to assess the predictive capability of the model for the year 2031, supplementary statistical data were analyzed, as presented in Table 11. The statistical measures included in this analysis were AIC, which demonstrated the minimum attainable value, and R2, which surpassed a threshold of 0.8. These indicators demonstrate a significant level of confidence in the model's capacity to reliably forecast Land Surface Temperature (LST). In addition, the statistical insignificance of the Koenker statistic (BP) serves to further support the stability and compatibility of the model that has been developed.

Table 11. Validation of the GWR Model for Predicting LST in 2031

Akaike's Information Criterion (AICc)	**Adjusted R-Squared**	**Koenker (BP) Statistic**
26.793421	0.88947	0.752355

The findings of this study indicate that Geographically Weighted Regression (GWR) has superior compatibility and stability in model construction when compared to Ordinary Least Squares (OLS). Therefore, the use of GWR was adopted for the purpose of predictive modeling. Table 12 displays the comparative analysis of the GWR and OLS models.

Table 12. Comparison of GWR and OLS Models

Regressions	**Akaike's Information Criterion (AICc)**	**Adjusted R-Squared**
OLS	26.793421	0.858944
GWR	21.675436	0.9158433

Following a thorough assessment of the correctness of the developed model and a careful examination of the relevant independent factors pertaining to the urban heat islands of Tehran, the Land Surface Temperature (LST) levels for the year 2031 were projected utilizing the Geographically Weighted Regression (GWR) technique. Figure 15 depicts the computed Land Surface Temperature (LST) for the calendar year 2021, whilst Figure 16 showcases the projected LST for the year 2031.

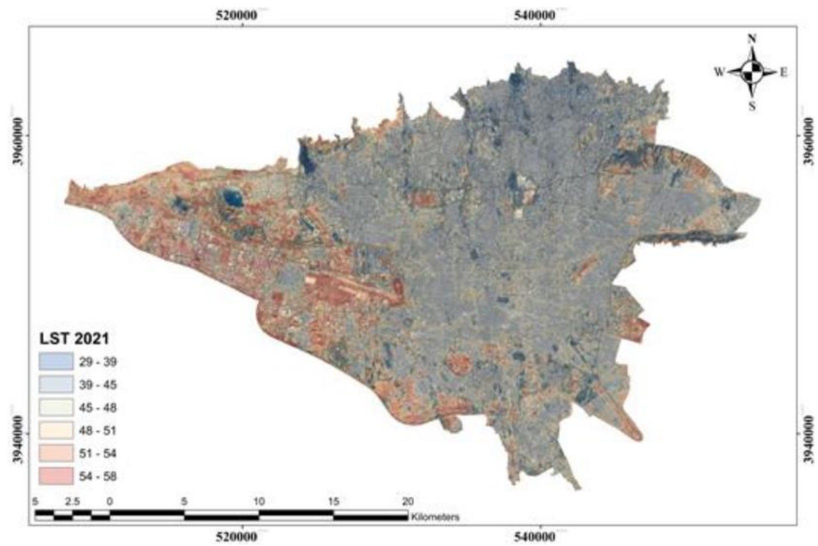

Figure 15. Map of Calculated LST for the Year 2021

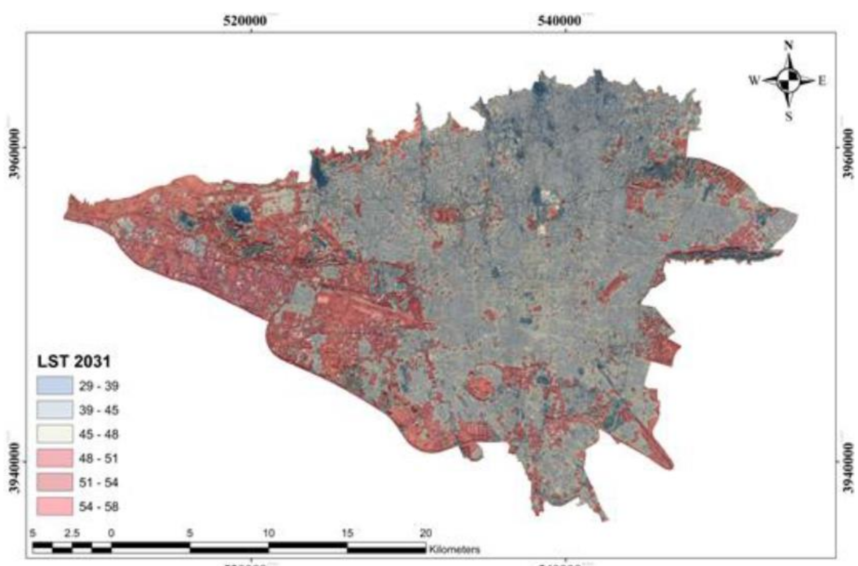

Figure 16. Map of Predicted LST for the Year 2031

6. Conclusions

The objective of this study was to examine the spatial distribution of urban heat islands and analyze the environmental elements that contribute to their formation through modeling. A unique study was conducted in the field, utilizing a mix of remote sensing (RS), geographic information systems (GIS), and spatial statistical approaches. This approach differs from past research in the subject. The examination of many elements that impact urban heat islands is an essential undertaking in the effort to alleviate urban heat stress and advance sustainable urban design. The prioritization of environmental health and well-structured planning in cities is crucial for enhancing the quality of life for its citizens, given that cities serve as human living places.

In the initial phase of our study, we employed satellite imagery from Landsat 8 and Landsat 5 to determine land surface temperatures (LST) for route 164 and row 35. In order to ascertain the precision and reliability of our research, we performed an examination of the generated Land Surface Temperature (LST) maps within the designated geographical region. To facilitate a concrete comparison of land surface temperatures across various land use types, five distinct locations within the city of Tehran were selected. These locations encompass a range of land uses, including green spaces, built-up regions, bare ground, and water. The findings of the study suggest that in the vicinity of the Persian Gulf, the urban heat island effect is less pronounced in areas with water bodies, such as the Persian Gulf and its associated water amenities. This can be attributed to the less absorption of solar heat by water, leading to lower temperatures in these areas. In a similar vein, Kuh-e-Sar Park exhibited decreased temperatures, which may be linked to its abundant plant cover. The presence of greenery facilitates evapotranspiration processes, so contributing to the mitigation of heat.

The arid regions including the Persian Lake Gulf, Mehrabad Airport, and Valiasr Park exhibit high temperatures in concentrated places as a result of the presence of asphalt surfaces and limited moisture permeability. As a result, there was an elevation in heat transfer and an enhanced capacity for moisture retention. Additional examination was undertaken to analyze the risk clusters and comparatively less risky urban heat islands, utilizing the global Moran's I test for spatial autocorrelation and the local Moran's I test for hot spot and cold spot analysis. Based on the aforementioned analysis, it was determined that there exists a notable geographical clustering pattern of urban heat islands in the city of Tehran. In the research area, regions exhibiting land surface temperatures with a confidence level over 95% were seen to cluster predominantly in the northern and northwestern sectors. Conversely, areas characterized by land surface temperatures associated with higher risk were found to be dispersed in the western and southwestern portions of the study area.

Furthermore, the implementation of urban zoning was based on the spatial distribution pattern of these clusters of danger. Following the process of zoning, it was ascertained that the regions exhibiting the greatest land surface temperatures were situated in the western and southwestern sectors of Tehran city, next to the study area. After the discovery of these relevant variables, a statistical analysis was conducted to ascertain the significance of the variables in influencing land surface temperature (LST). The study examined various variables, including elevation, NDVI (Normalized Difference Vegetation Index), NDBI (Normalized Difference Built-Up Index), solar radiation, slope, aspect, and CO2. Ordinary least squares (OLS) regression was employed to identify the significant factors that contribute to the formation of urban heat islands in Tehran. The findings of the research indicate that there is a substantial relationship between three independent variables, namely NDVI, elevation, and NDBI, and the Land Surface Temperature (LST) in Tehran. The correlation between the elevation variable and the relationship intensity is somewhat less in comparison to the other two variables. Additionally, it has been shown that there is a positive correlation between the reduction of plant cover and the expansion of built-up regions, leading to an increase in land surface temperature (LST) levels. The measure known as Normalized Difference Built-up Index (NDBI) has a positive correlation with Land Surface Temperature (LST), indicating that an expansion of built-up regions leads to an elevation in the severity of the urban heat island effect. Nevertheless, it is worth noting that both the variables of vegetation cover and elevation have inverse correlations with land surface temperature (LST). The correlation between the vegetation cover variable and land surface temperature (LST) is more pronounced when compared to the other two variables. This suggests that the vegetation cover variable exerts the most significant impact on mitigating the formation of urban heat islands in Tehran. The results indicate that all three factors had a statistically significant association with LST.

In order to assess the suitability of the geographically weighted regression (GWR) model for forecasting land surface temperature (LST) in the year 2031, we conducted an examination of many statistical variables. The GWR model was shown to have more stability and adaptability in performance when compared to the ordinary least squares (OLS) model. Consequently, the decision was made to employ the GWR regression model for predicting land surface temperature (LST) in the year 2031.

In its whole, this study enhances the collective comprehension of urban heat islands and their geographical distributions in the city of Tehran. The integration of remote sensing, geographic information systems (GIS), and spatial statistical methodologies facilitated the identification of relevant elements and the precise prediction of land surface temperature (LST). This knowledge is of utmost importance for the field of urban planning and for effectively addressing the issue of heat stress among urban people in Tehran.

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