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Modeling Vegetation Cover Maps Affecting Land Surface Temperature in Erbil City Using Remote Sensing

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ABSTRACT

This study aims to monitor and analyze vegetation cover and its impact on land surface temperature (LST) in Erbil City over the period 1990–2023. The research utilizes JavaScript programming within the Google Earth Engine (GEE) platform to acquire satellite imagery for both vegetation cover (NDVI) and LST. Extracted temperature data were classified using internationally recognized standards and further processed within a Geographic Information System (GIS) environment. Advanced cartographic modeling techniques were applied to generate LST classification maps throughout the study period.

The results reveal a significant rise in land surface temperatures across Erbil City. Warm zones accounted for 34.8% of the total area, hot zones covered 37.6%, and very hot zones made up 27.7%. These findings underscore the substantial impact of rising temperatures on the urban environment and overall quality of life, highlighting the urgent need for sustainable environmental planning and urban heat mitigation strategies.

نمذجة خرائط الغطاء النباتي المؤثر على درجة حرارة سطح الأرض في مدينة اربيل باستخدام الاستشعار عن بعد

سعد ثامر ابراهيم ، حمده حمودي شيت ، فائق حسن محيميد
قسم الجغرافية ونظم المعلومات الجغرافية , كلية الآداب , جامعة تكريت , العراق

الخلاصة

يهدف البحث الى رصد ومراقبة الغطاء النباتي المؤثر على درجة حرارة سطح الأرض في مدينة اربيل للفترة 1990 - 2023، وذلك من خلال الاستعانة بأكواد لغة البرمجة JavaScript داخل منصة (Google Earth Engine) التي تتيح امكانية تحميل مرئيات فضائية خاصة بالغطاء النباتي وبدرجة حرارة سطح الارض Lst في منطقة الدراسة، ومن ثم نخضع بيانات LST التي تم استنتاجها من المنصة وفق معايير عالمية خاصة من اجل تصنيفها الى مستويات والعمل عليها داخل بيئة برنامج نظم المعلومات الجغرافية، ومن ثم العمل على نمذجة خريطة اصناف درجة حرارة سطح الأرض للفترة 1990-2023 باستخدام مجموعة من الطرائق الخرائطية المتقدمة وفق معايير خرائطية خاصة، وأظهرت النتائج أن مدينة أربيل تواجه تحديات ملحوظة بسبب الارتفاع المتزايد في درجات الحرارة، وبلغت نسبة مساحة المناطق الدافئة خلال فترة الدراسة (34.8 %)، والمناطق الحارة (37.6 %)، اما المناطق الحارة جداً (27.7%)، وهذا بدوره يؤثر بشكل كبير على البيئة الحضرية وجودة الحياة.

الكلمات المفتاحية: درجة حرارة سطح الأرض،خرائط المكعبات الحجمية ، الغطاء النباتي ، مدينة أربيل،الاستشعار عن بعد

INTRODUCTION

Modeling vegetation cover maps is a vital scientific approach to understanding the relationship between vegetation dynamics and their influence on land surface temperature (LST), particularly in urban environments undergoing significant ecological transformations. Erbil City serves as a representative case study, having experienced notable environmental and urban changes between 1990 and 2023 that have directly affected vegetation patterns and surface temperature levels.

This study employs Geographic Information Systems (GIS) and Remote Sensing (RS) technologies to analyze spatial and environmental data, with the objective of producing precise models that illustrate how variations in vegetation cover influence LST. The significance of this modeling lies in its ability to provide empirical insights that inform sustainable urban planning, environmental policy, and climate resilience strategies in Erbil.

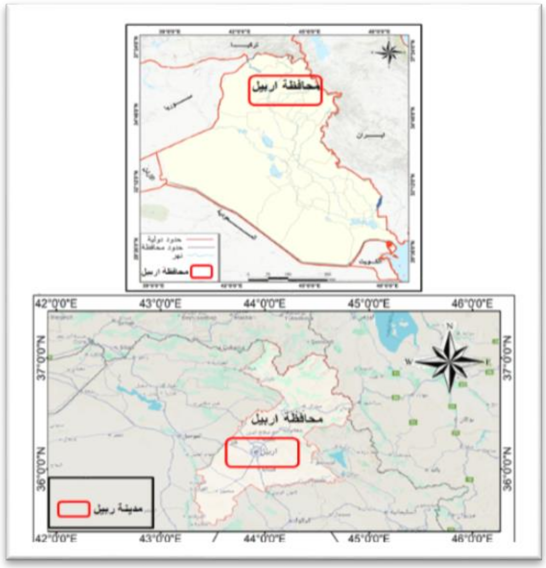
The research integrates satellite-derived vegetation and LST datasets using the Google Earth Engine (GEE), a cloud-based geospatial analysis platform. Through JavaScript programming, NDVI and LST imagery were acquired, processed, and classified. These datasets were then integrated within a GIS framework to generate high-resolution thematic maps. Advanced cartographic techniques were used to analyze spatiotemporal changes across the 33-year study period. This study addresses the following research questions: How can remote sensing, specifically the GEE platform, be utilized to extract and analyze NDVI and LST data for Erbil City between 1990 and 2023? What is the quantitative relationship between vegetation cover and surface temperature across time? How can multi-temporal LST classification maps be developed using GIS and remote sensing techniques? The study hypothesizes that the use of satellite data, processed through remote sensing and GIS technologies, can effectively model and quantify the impact of vegetation cover on land surface temperature. It further assumes that urban expansion and vegetation loss significantly contribute to rising surface temperatures in Erbil.

To achieve its objectives, the study adopts an analytical and inductive methodology, combining technical workflows in GEE with spatial analysis in ArcGIS Pro and ArcMap. This integrated approach provides a comprehensive spatial assessment of vegetation and temperature dynamics in Erbil City over time.

MATERIAL AND METHODS

Study Area:

The study area is located in the northeastern part of Iraq and forms the central region of the Kurdistan Region. Geographically, it extends between latitudes 34°18′ to 36°05′ N and longitudes 43°54′ to 44°09′ E. It is bordered by Ain Kawa and Baharka to the north, Dara Tu to the south, Khasnzan to the east, and Rzkar to the west, as illustrated in Map 1.



Map (1) Location of the study area

This study employed a comprehensive methodology integrating remote sensing data, GIS tools, and spatial modeling techniques to analyze vegetation cover and land surface temperature (LST) in Erbil from 1990 to 2023. The following datasets and software platforms were used:

1. Data Sources and Software Tools: Satellite Imagery was obtained from the Google Earth Engine (GEE) platform, including data from Landsat, MODIS, and Sentinel satellites. NDVI and LST data were processed using JavaScript programming within GEE. Spatial data analysis was conducted using ArcMap 10.8 and ArcGIS Pro 3.0, developed by Esri. Statistical and temporal analysis was supported by Microsoft Excel 365, and Python 3.10 was used for additional data visualization.

2. Vegetation and Temperature Data Processing: Normalized Difference Vegetation Index (NDVI) was computed using the standard formula: **NDVI=(NIR−RED)(NIR+RED)NDVI=\frac{(NIR-RED)}{(NIR+RED)}NDVI=(NIR+RED)(NIR−RED)** where NIR and RED represent near-infrared and red reflectance, respectively (Zhang *et al*., 2020). **Land Surface Temperature (LST) data were extracted from thermal infrared bands and processed according to global classification standards into:** Warm (25°C–30°C); Hot (30°C–35°C); and Very Hot (>35°C)

NDVI data were classified into four categories: No vegetation (NDVI < 0.1), Low vegetation (0.1–0.3), Moderate vegetation (0.3–0.5), and Dense vegetation (>0.5)

3. Remote Sensing Techniques: GEE was utilized to download and process NDVI and LST images across multiple time intervals. JavaScript automation enabled batch processing and trend analysis from 1990 to 2023, ensuring temporal consistency. NDVI, VCI, and VHI indices were used to analyze vegetation dynamics and health (Rahman & Lee, 2021; Hassan *et al*., 2022).

4. GIS and Spatial Modeling: GIS-based spatial overlay and raster classification were used to map vegetation and LST categories. Grid-based interpolation and 3D topographic visualization were used to model spatial relationships using elevation and thermal intensity. Overlay analysis helped identify spatial correlations between NDVI and LST across urban and vegetated zones.
5. Analytical Techniques: Time-Series Analysis was used to detect long-term vegetation and temperature trends. Inductive Reasoning supported the transition from detailed observations to broader generalizations about environmental changes. The study also incorporated geostatistical analysis to assess spatial variability and clustering patterns.
6. Ethical Compliance and Standards: The study did not involve human or animal subjects; however, data handling followed scientific integrity and spatial data ethics protocols. All measurements adhered to metric units and international scientific standards.

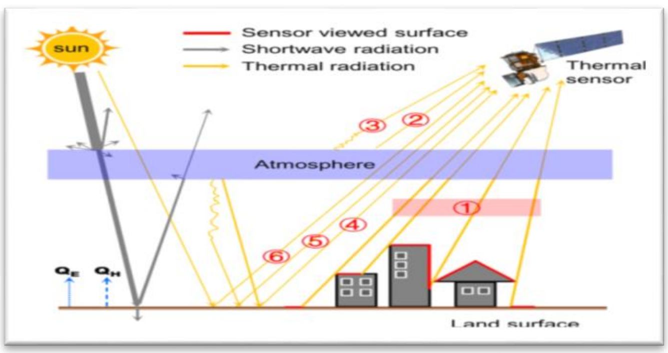


Figure (1): Infrared Radiation Captured by Satellite Sensors.

Figure (1) illustrates a set of radiative pathways associated with remote sensing. The first pathway represents radiation emitted directly from the surface of the target, while the second pathway refers to the upward thermal radiation from the atmosphere. The third pathway represents scattered solar radiation as it ascends through the atmosphere, whereas the fourth pathway involves downward atmospheric thermal radiation. The fifth pathway shows downward scattered solar radiation, and the sixth pathway depicts direct solar radiation reflected from the surface. Before these radiations reach the sensor, they undergo attenuation due to the atmosphere. Among these pathways, the first pathway is most closely related to land surface temperature (LST) and the targeted emissivity, while radiations associated with solar energy are generally neglected. The third, fifth, and sixth pathways related to solar energy have a minimal effect on retrieving LST, owing to the thermal infrared window, which lies within wavelength ranges of 8 to 14 micrometers and 3 to 5 micrometers (Li, Z.; Tang, B.; Wu, H.; Ren, H.; Yan, G.; Wan, Z.;2013).
Below are some Google Earth Engine codes that can be used to monitor and track heat islands ,This link provides access to interactive cartographic models for land surface temperature (LST) and vegetation cover (NDVI) in Erbil city from 1990 to 2023, as shown in figure (2).

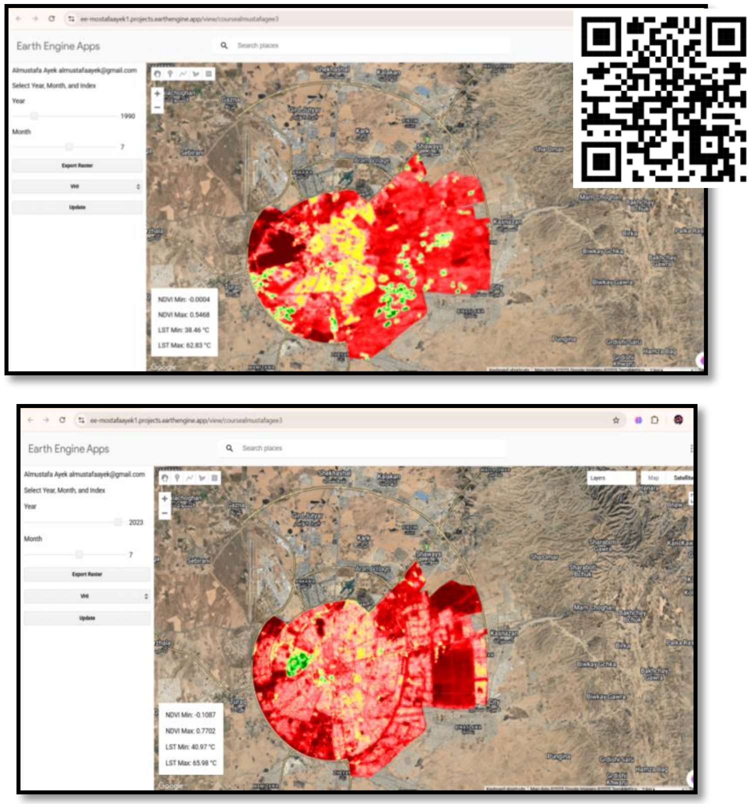


Figure (2): Interactive cartographic models for vegetation cover (NDVI) and land surface temperature (LST) in Erbil city from 1990 to 2023

RESULTS AND DISSCUSION

Monitoring and distinguishing vegetation cover (NDVI) and land surface temperature (LST) are among the most important environmental applications of remote sensing, as this technology provides effective tools for analyzing environmental changes on a large scale with high precision. The Normalized Difference Vegetation Index (NDVI) is used as a tool to measure the density and health of vegetation based on the ability of plants to absorb light in the red spectrum and reflect it in the near-infrared range. Conversely, LST data is derived from thermal radiation emitted by the Earth's surface, allowing for the assessment of the impacts of climate, human activity, and environmental changes on the thermal balance of the region. The combined use of these two indicators through remote sensing provides a comprehensive view of the relationship between vegetation cover and temperature, aiding in the understanding of ecosystem dynamics and supporting sustainable decision-making for natural resource management and mitigating negative environmental changes.

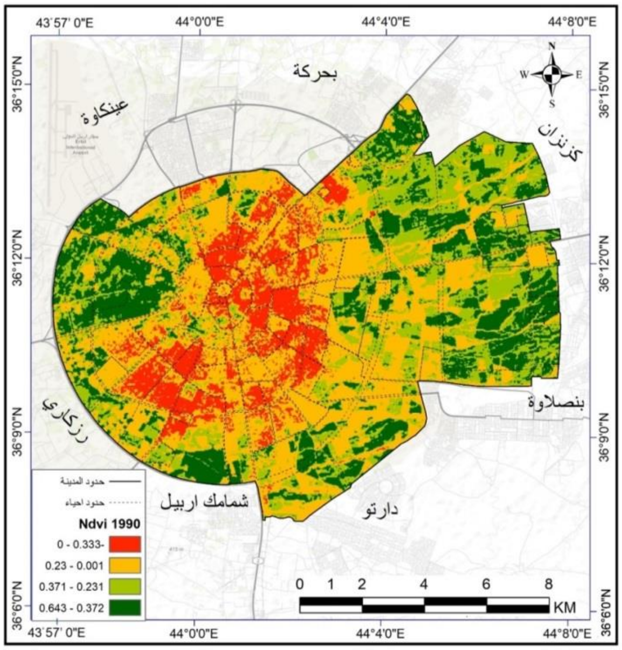
Google Earth Engine (GEE) is one of the most powerful cloud-based platforms specialized in the analysis of remote sensing data and satellite imagery. This platform provides easy access to a large and diverse set of satellite data such as Landsat, MODIS, and Sentinel, making it an essential tool for researchers and specialists in the fields of geography and remote sensing. GEE is distinguished by its high capabilities in spatial and temporal data analysis using advanced programming languages such as JavaScript and Python, allowing users to perform complex analyses efficiently and quickly. Additionally, the platform supports work over broad time scales, enabling researchers to study environmental and climatic phenomena and their development over time. GEE is ideal for studying environmental indicators such as vegetation cover (NDVI) and land surface temperature (LST) due to its high capabilities in processing data rapidly and efficiently through cloud computing.

To monitor and track vegetation cover and land surface temperature using the Google Earth Engine (GEE) platform, its advanced capabilities for analyzing spatial and temporal data can be leveraged. The platform provides an easy-to-use interface that allows developers to access a vast database of geographic data and online analytical tools. In this context, the platform was used to extract vegetation cover and LST images covering the period from 1990 to 2023. The GEE platform offers users the ability to use JavaScript to develop custom applications for environmental and geographic monitoring, benefiting from a variety of available geographic tools and data.

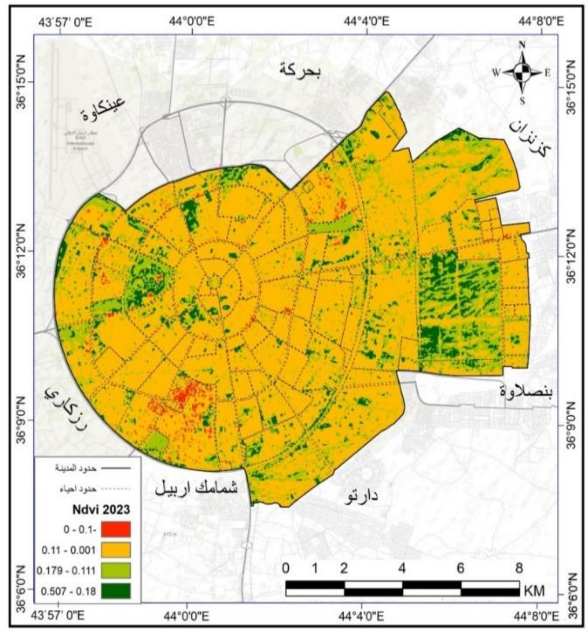
Vegetation cover maps are a vital tool in understanding the distribution of vegetation (NDVI) in the study area. The process of creating vegetation cover maps begins with collecting the necessary data through satellite imagery and using specific equations. Different colors are used to represent various types of vegetation, which helps in distinguishing areas. For example, dark green is used for dense vegetation, and light green for low-density vegetation. Vegetation is a significant factor affecting the climatic characteristics of the urban heat island, as it reduces the reflection of sunlight from the Earth's surface, thereby lowering temperatures. Plants absorb most of the solar radiation falling on them for photosynthesis and help cool the surrounding air through a process called transpiration, where they release water vapor into the atmosphere, leading to a decrease in air temperature. Additionally, vegetation helps reduce the speed of surface winds, which mitigates the transfer of heat from the ground to the atmosphere. Plants also act as thermal insulators, preventing heat from reaching the soil. By increasing air humidity through transpiration, vegetation leads to lower air temperatures due to increased humidity. Therefore, vegetation plays a crucial role in regulating surface temperatures, reducing high temperatures in hot areas and increasing them in cold areas (Qahhtani, R. M. ,2020).

Grasslands have significant importance within their growth zones, as they form a protective cover that reduces ultraviolet radiation and the direct impact of hot solar radiation, thus lowering the surrounding area's temperature. Plants cool the environment through a process called "vegetative evaporation," where plants absorb water from the soil and release it into the atmosphere through their leaves, contributing to the cooling of the air. Some steppe plants can also increase the humidity in the air, which in turn can influence temperatures. Furthermore, steppe grasses can provide natural shade under the sun, reducing the effects of direct sunlight and alleviating heat.

The region experiences rainfall during the winter, which has contributed to the emergence of various natural plant species. Seasonal steppe plants are the most widespread, as they begin to grow during the rainy season in spring, only to wither and dry out at the onset of the dry season. Prominent among them are the short grasses. Wetland plants also grow, spreading along the tributaries and branches across the city, with reed plants growing in the beds and banks of valleys. The impact of vegetation cover on land surface temperature in the study area was studied over five periods from 1990 to 2023 as follows:
Vegetation Cover (NDVI) for 1990 :



Map (2): Vegetation (NDVI) for the year (1990)



Map (3): Vegetation (NDVI) for the year (2023)

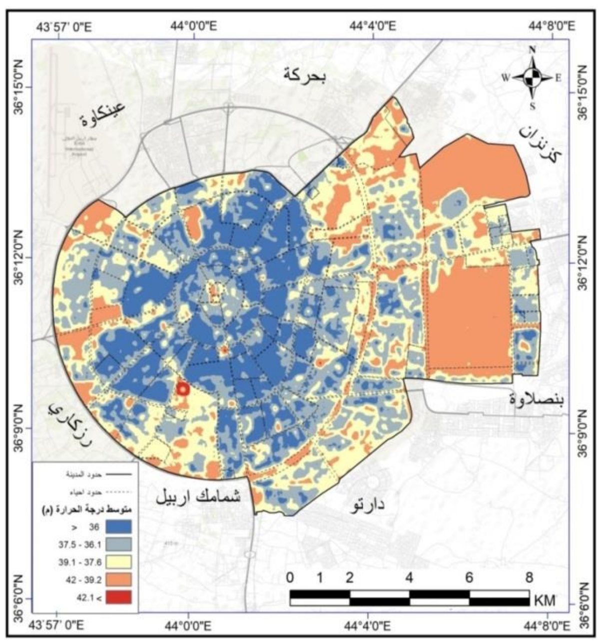


Figure (4): Land Surface Temperature (LST) for the period 1990–2023

The cartographic visualization of the "Vegetation Cover Maps" shows the distribution of vegetation in the study area using the Normalized Difference Vegetation Index (NDVI) for the period (1990–2023). The maps illustrate the diversity of vegetation over a broad range, facilitating a detailed understanding of the distribution and botanical characteristics of the area. Colors were effectively utilized to represent different levels of vegetation cover, with dark green indicating high vegetation density, yellow representing moderate cover, and red indicating areas with sparse or no vegetation. Furthermore, color gradients were applied to enhance the clarity of differences between various vegetation levels, making it easier to identify the most fertile areas and those with diminished vegetation. In terms of map aesthetics, the color scheme is well-balanced, making the information easy on the eyes. The good coordination between colors and labels improves the visual experience for the viewer.

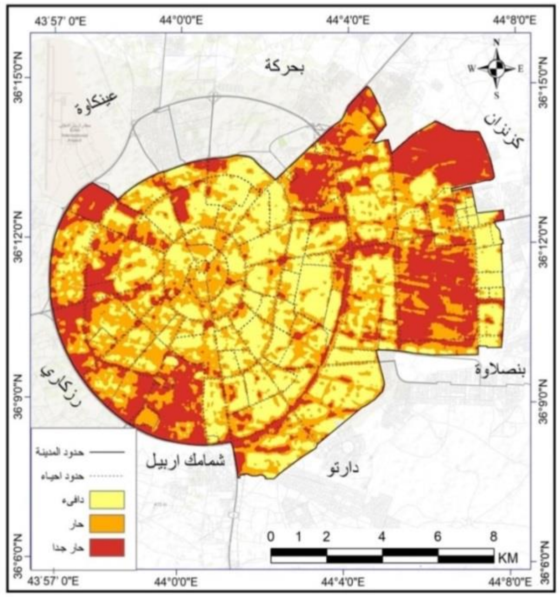
The map represents the average land surface temperature (LST) distribution in Erbil City, categorizing temperature levels using a color gradient. The blue shades represent cooler areas, while yellow to red shades indicate progressively hotter areas.
The central and western parts of the city predominantly show blue regions, which suggests that these areas experience relatively lower surface temperatures, likely due to the presence of vegetation, water bodies, or shaded urban infrastructure. The peripheral and eastern parts of the city, particularly in Binislawa and surrounding areas, are covered in orange to red shades, indicating higher land surface temperatures exceeding 39°C to 42°C. These regions may have fewer green spaces, more exposed urban surfaces, or industrial zones that contribute to increased heat absorption.

A notable observation is that scattered patches of high temperatures (red) appear within the blue areas, which could be hotspots caused by dense urbanization, lack of vegetation, or heat-absorbing surfaces like asphalt and concrete. Similarly, transitional zones with yellow and light orange colors suggest areas where temperature fluctuations occur due to mixed land use, including residential, commercial, and undeveloped land.
Comparing this map with NDVI maps of different years (1990–2023) suggests that areas with higher vegetation cover tend to have lower temperatures (blue regions), while areas with reduced vegetation exhibit higher temperatures (orange-red regions). This emphasizes the significant role of vegetation and green spaces in mitigating urban heat islands (UHI) and improving microclimate conditions.

Future urban planning strategies should focus on expanding green spaces, using reflective building materials, and enhancing urban cooling measures to mitigate high surface temperatures in critical heat zones. Further studies comparing seasonal LST variations can help in developing more sustainable climate adaptation policies for Erbil City.

1. Temporal Trends in Vegetation Cover:

- In 1990, there was a clear diversity in vegetation cover, with moderate and dense vegetation covering 45.4% of the total area. This contributed to lower land surface temperatures.
- In 2000, the city experienced a significant deterioration in vegetation cover, with non-vegetated areas increasing to 62.4%, leading to a rise in surface temperature due to increased solar radiation absorption.
- By 2010, vegetation cover showed some improvement, as non-vegetated areas decreased to 32.6%, while moderate and dense vegetation increased to 33.4%, helping to regulate local temperatures.
- In 2020, Erbil witnessed a substantial recovery, with non-vegetated areas dropping to 0.7% and low vegetation areas expanding significantly (68.8%), possibly due to afforestation efforts or favorable climate changes.
- In 2023, the upward trend in vegetation cover continued; however, dense vegetation areas declined to 7.1% compared to 2020, indicating potential land-use changes or environmental factors.



Map (5): Land Surface Temperature (LST) Classes in Erbil City for the period 1990 - 2023

The map represents the land surface temperature (LST) distribution in Erbil City, using a color-coded classification to illustrate variations in temperature levels. The yellow areas indicate moderate heat zones, while red and dark red areas represent high-temperature zones with intense heat accumulation.

A clear pattern emerges, where hot and very hot areas (red and dark red) are concentrated in the outskirts of the city, particularly in the eastern and southwestern regions. These areas likely experience higher land surface temperatures due to a combination of urbanization, lack of vegetation, and the presence of industrial or commercial zones. The central and inner parts of the city, though still warm, exhibit a mix of moderate heat zones, possibly due to higher building density providing shade and localized cooling effects.

The widespread presence of high-temperature zones suggests that urban heat island (UHI) effects are prominent, where urban materials such as concrete and asphalt retain more heat compared to natural surfaces. Additionally, the low vegetation cover in these areas exacerbates heat accumulation, as seen in previous NDVI maps of Erbil.

This thermal analysis highlights the urgent need for climate adaptation strategies, such as increasing urban greenery, implementing reflective surfaces, and enhancing water-based cooling systems. A comparative assessment with historical temperature maps would provide further insights into how urban expansion has influenced temperature trends over time.

Grid cells mapping is one of the methods used to represent spatial distributions, as it involves dividing the geographical area into a regular grid of squares (pixels). Each square represents a specific value or classification of the data (Ibrahim. & Mahmoud, (2020), making it an independent analytical unit that reflects the studied phenomenon, such as thermal values or vegetation density in that section of the map. This approach adds height to these squares, turning them into a 3D representation. This method helps in facilitating the understanding and analysis of spatial patterns in a precise and organized manner. Consequently, grid cell maps assist in analyzing the spatial relationships between variables, simplifying the display of large datasets. They are also used in environmental assessments, urban planning, and studying spatial patterns in an easy-to-understand and accurate way, making them an effective tool for environmental and administrative decision-making. A 3D grid cell map was modeled for the land surface temperature (LST) categories in the study area for the period (1990-2023), and alignment was performed with the high spatial accuracy satellite imagery of Erbil City. Green areas within the city were drawn using the satellite data, and a Mix operation was performed between the green areas and LST categories within the study area.

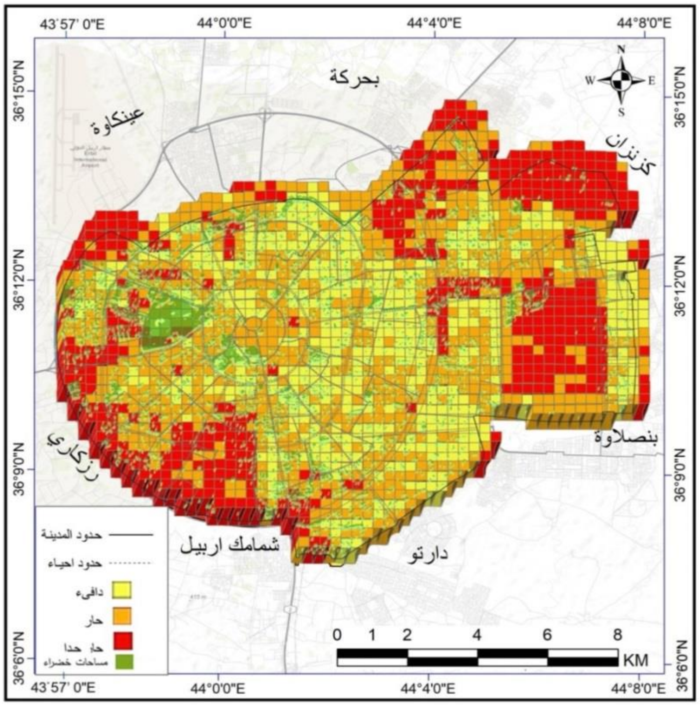


Figure (6): Using 3D grid cell maps in modeling land surface temperature (LST) categories with green areas in the study area for the period (1990-2023).

The table represents the distribution of vegetation cover in Erbil City, showing the percentage of each vegetation category relative to the total area of 141 km². The data indicate that more than 54.6% of the area consists of low or no vegetation, suggesting vast urban zones or barren lands that are not utilized for agriculture. This condition may contribute to increased land surface temperatures and the intensification of the urban heat island effect. On the other hand, areas with moderate or dense vegetation account for approximately 45.4% of the total area, reflecting the presence of green spaces and agricultural lands that play a crucial role in improving air quality and mitigating climate change effects. However, the proportion of densely vegetated areas remains relatively low compared to zones experiencing vegetation loss or degradation, emphasizing the need for environmental strategies to enhance afforestation and increase green spaces in urban and suburban areas. It can be concluded that areas with low vegetation cover require sustainable environmental interventions to expand green areas and restore ecological balance, particularly given the rapid urban expansion. Promoting urban afforestation and implementing land reclamation projects can help mitigate global warming effects and improve the city's local climate, ensuring a more sustainable urban environment for the future.

Table (1) Vegetation Cover (NDVI) for 1990

Category	Map Color	Area (km²)	Percentage (%)
No vegetation	Red	18	12.8
Low vegetation	Yellow	59	41.8
Moderate vegetation	Light Green	35	24.8
Dense vegetation	Dark Green	29	20.6
Total		141	100.0

Source: Based on map (2).

Table (2): Vegetation (NDVI) for the year (2023)

Category	Map Color	Area (km²)	Percentage (%)
No vegetation	Red	2	1.4
Low vegetation	Yellow	102	72.3
Moderate vegetation	Light Green	27	19.1
Dense vegetation	Dark Green	10	7.1
Total		141	100.0

Source: Based on map (3).

The table represents the vegetation cover distribution in Erbil City, showing a continued shift in land use and vegetation patterns. The no vegetation category (1.4%) remains minimal, indicating that almost all previously barren lands have either been urbanized or converted into low vegetation zones. This suggests that while land degradation has been somewhat controlled, urban expansion and infrastructure development may still be contributing to vegetation loss. The low vegetation category (72.3%) has increased, covering nearly three-quarters of the total area. This indicates a predominance of sparse vegetation, scattered greenery, and low-density plant cover, which, while beneficial, does not provide the same climatic and ecological advantages as dense vegetation. The spread of low vegetation could be attributed to seasonal crops, grasslands, or urban green patches, but it also highlights a lack of significant afforestation or dense urban forests. The moderate vegetation category (19.1%) and dense vegetation category (7.1%) together account for 26.2% of the total area, showing a slight decline in dense vegetation compared to previous years. The reduction in dense vegetation suggests that either deforestation, urbanization, or climate stressors may be contributing to a decrease in tree cover and high-density vegetation zones. These findings indicate that while vegetation cover persists, it remains mostly low-density, meaning that the city's ability to regulate temperatures, improve air quality, and sustain biodiversity is still limited. Urban greening initiatives, reforestation programs, and sustainable land management policies should be prioritized to reverse the decline in dense vegetation and enhance ecological resilience in Erbil City.

Table (3): Land Surface Temperature (LST) for the period 1990 - 2023

Percentage (%)	**Area (km²)**	**Legend Color**	**Average Temperature (°C)**
20.6	29	Dark Blue	>36.0
29.8	42	Light Blue	36.1 - 37.5
27.7	39	Light Yellow	37.6 - 39.1
21.3	30	Light Red	39.2 - 42.0
0.7	1	Dark Red	>42.1
100.0	141		TOTAL

Source: Based on Figure (4).

The table presents the spatial distribution of average land surface temperature (LST) in Erbil City, illustrating temperature variations across different areas. This data helps in understanding the impact of urbanization and vegetation cover on the local climate. The figures indicate that nearly half of the city (49%) experiences temperatures exceeding 37.6°C, highlighting the urban heat island (UHI) effect caused by urban expansion and the use of heat-retaining materials such as asphalt and concrete. Moderate temperature zones, with LST below 37.5°C, cover approximately 50.4% of the total area, suggesting that these areas may include vegetation, agricultural lands, or other cooling factors that help lower surface temperatures. In contrast, the hottest areas (>42.1°C) are concentrated in industrial and densely built commercial zones, where infrastructure and high building density significantly contribute to rising temperatures. This distribution highlights the importance of sustainable urban planning, where strategies such as expanding green spaces, using reflective building materials, and developing environmentally friendly infrastructure can help mitigate high temperatures and improve the city's overall livability. Comparing this data with past and future LST trends can provide a clearer understanding of temperature changes over time, aiding in the development of long-term strategies for climate change mitigation and urban heat adaptation.

The classification of urban LST levels represents the spatial and temporal variability of the phenomenon in Erbil city, illustrating how the intensity and impact of heat change in the city based on location and time. From this (C. Yu, W.N. Hien,2012), Land Surface Temperature can be classified according to the temperature levels as shown in Table (4).

Table (4): Classification of Heat Island Patterns (Roth, M,2007)

Description	**(°C) Temperature Description**	**Categories**
Areas with low temperatures, typically occurring in winter or at night.	Below 10	Cold
Areas with comfortable temperatures, usually in transitional seasons (spring and autumn.(	10 – 20	Moderate
Areas with warm temperatures, generally during the day in spring, autumn, or summer nights.	20 – 30	Warm
Areas with high temperatures, mostly occurring during summer days.	30 – 40	HOT
Areas with extremely high temperatures, typically during very hot summer days.	Above 40	VERY HOT

Table (5): Land Surface Temperature (LST) Classes in Erbil City for the period 1990 - 2023

%	Area (km²)	Map Color	Land Surface Temperature Classes
34.8	49	Yellow	Warm
37.6	53	Orange	HOT
27.7	39	Dark Red	VERY HOT
100	141		TOTAL

Source: Based on Map (5)

The table presents the land surface temperature (LST) classification for Erbil City, highlighting the distribution of temperature zones across the area. The data indicate that the city is predominantly affected by high temperatures, with over 65% of the total area classified as "Hot" or "Very Hot". The Warm category (34.8%) covers 49 km², representing areas with moderate temperature levels, typically occurring in spring, autumn, or summer nights. These zones may have some vegetation cover or lower urban density, helping to keep surface temperatures relatively stable. The Hot category (37.6%) extends across 53 km², making it the largest temperature zone in the city. These areas experience high daytime temperatures, particularly in summer, and are likely urbanized regions with heat-absorbing surfaces like concrete and asphalt. The lack of significant vegetation and cooling infrastructure in these zones contributes to higher urban heat island (UHI) effects.

The Very Hot category (27.7%), covering 39 km², represents areas experiencing extreme heat conditions, where temperatures exceed 40°C during peak summer periods. These zones are highly vulnerable to heat stress, energy overuse for cooling, and environmental degradation. The presence of industrial areas, dense urban zones, and limited vegetation likely contributes to the heat retention in these regions. This data underscores the pressing need for sustainable urban cooling strategies, including expanding green spaces, increasing tree cover, adopting heat-reflective materials, and implementing water-based cooling solutions. A comparative analysis with past LST maps could provide insights into how urbanization has impacted temperature trends and guide future climate adaptation policies to mitigate extreme heat in Erbil City.

CONCLUSION

This study effectively monitored and modeled the relationship between vegetation cover (NDVI) and land surface temperature (LST) in Erbil City for the period 1990–2023, utilizing the Google Earth Engine (GEE) platform and GIS technologies. The integration of satellite-derived imagery and advanced spatial analysis techniques enabled the development of accurate vegetation and LST maps, which revealed significant environmental changes over time. The results show a clear trend of increasing surface temperatures in Erbil, with substantial urban heat island (UHI) effects. The city has experienced a dramatic loss of dense vegetation, with the proportion of low vegetation significantly increasing over the years. This reduction in vegetation has contributed to higher surface temperatures, which are particularly pronounced in the city’s industrial and less vegetated areas. In the study period, approximately 65% of Erbil's total area was categorized as hot or very hot, highlighting the pressing challenge of managing thermal dynamics in the city. The findings emphasize the need for urban policies that prioritize environmental sustainability, including expanding green spaces and promoting urban cooling strategies to mitigate the effects of rising temperatures.

RECOMMENDATIONS

Based on the findings of this study, several recommendations are proposed to address the increasing surface temperatures and enhance the environmental resilience of Erbil: Increase Green Spaces: It is essential to expand and improve urban green spaces to counteract the UHI effect. Afforestation programs, tree planting, and the development of urban parks and green roofs should be prioritized to enhance vegetation cover and reduce surface temperatures. Use of Heat-Reflective Materials: The use of reflective or cool materials in urban infrastructure, such as pavements, roofing, and facades, can significantly lower surface temperatures. Such materials help reflect sunlight rather than absorb heat, thereby reducing thermal stress in urban areas. Urban Cooling Strategies: Development of urban cooling systems, including water-based cooling techniques (e.g., fountains, urban lakes) and the promotion of green architecture, should be implemented to improve the microclimate in densely populated areas. Sustainable Land-Use Planning: Future urban planning should incorporate climate resilience strategies that balance urban expansion with the preservation of natural vegetation. Zoning regulations could encourage green spaces and reduce the development of heat-retaining surfaces in critical areas. Periodic Thermal Monitoring: Establishing a thermal monitoring network utilizing remote sensing and satellite data, such as those available from GEE, can help track long-term temperature trends in Erbil. Periodic updates and analyses will enable informed decision-making in urban planning and climate adaptation. Integration of AI and Advanced Spatial Analysis: Leveraging artificial intelligence (AI) and advanced machine learning models can further enhance the accuracy and efficiency of analyzing vegetation and temperature dynamics. These tools can also provide future climate scenario projections, helping to develop proactive measures for climate change mitigation. Focus on Public Health and Energy Efficiency: The study suggests that the impacts of temperature increases on public health and energy demand should be studied further. Addressing the health risks associated with heat stress and increasing energy efficiency in buildings will be crucial for improving the quality of life for urban residents.

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