

Identification of Urban Heat Island Effect on Land Use Land Cover Changes

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ARTICLE INFO

Article history:

Received 5 August 2023

Received in revised form 27 September 2023

Accepted 5 October 2023

Available online 31 October 2023

Keywords:

Land Use Land Cover

Land Surface Temperature

NDVI

Urban Heat Island

ABSTRACT

The effect of urban heat island (UHI), characterized by higher temperatures in urban areas compared to surrounding rural areas, is a significant consequence of rapid urbanization. As cities continue to grow and attract more people, the UHI effect intensifies due to increased heat-absorbing surfaces and reduced green spaces. This can lead to various environmental and health issues, specifically affecting vulnerable populations. This study investigates the phenomenon of UHIs in the Kalutara district of Sri Lanka and examines the relationship between Land Use Land Cover (LULC) changes, urbanization, and the intensity of UHIs. Landsat satellite images from 1991, 2001, 2011, and 2021 were analyzed using Remote Sensing and Geographic Information System (GIS) techniques to create land Surface Temperature (LST) maps and LULC maps. The results show a significant expansion of urban areas and a reduction in green areas within the Kalutara district over the study period, accompanied by an increase in the intensity of UHIs. Regression analysis indicates a negative correlation between the percentage of green areas and LST, highlighting the cooling effect of vegetation. Conversely, a positive correlation is found between LST and the percentage of urban areas. The research demonstrates the spread of UHIs from limited urban centers in 1991 to larger urban areas and adjacent regions in 2021. The findings emphasize the need for sustainable land management practices, preservation of green areas, and effective urban planning strategies to mitigate the adverse effects of UHIs.

1 Introduction

The world population has been increasing steadily over the past few decades and is expected to continue growing. The current global population stands at 7.96 billion, with a growth rate of approximately 1.11% per year. It is projected to reach 10 billion by 2056 according to the United Nations (UN, 2022). Furthermore, 6 billion people reside in less developed countries, while 1.2 billion reside in more developed countries, including 54.7% of the world's population living in urban areas as of 2017. As per the UN's predictions, by 2030, 60% of the world's population, estimated to be 8.5 billion, will be classified as urban populations (UN, 2015). In 2016, there were 512 cities with a population exceeding one million, and this number is expected to increase by roughly 30% to 662 by 2030 (Mirzaei and Haghighat, 2010; UN, 2017).

Urbanization, which involves people moving from rural

areas to cities, has played a significant role in the world population's growth. As cities continue to expand, they attract more individuals seeking opportunities and amenities, resulting in a further rise in the urban population. The Urban Heat Island (UHI) effect refers to the phenomenon where urban areas experience higher temperatures compared to their surrounding rural areas (UN, 2018). This occurs due to the increased concentration of heat-absorbing surfaces such as concrete and asphalt, along with a lack of vegetation and green spaces that can help cool the air. The UHI effect can have substantial impacts on land use, land cover changes, and urbanization. Urbanization can exacerbate the UHI effect by increasing impermeable surfaces and reducing green spaces, thereby heightening the risk of heat-related health problems, particularly for vulnerable populations such as the elderly and those with pre-existing health conditions (Zhang et al., 2012).

Urbanization can also contribute to Land Use and Land Cover (LULC) changes in developing countries, often resulting in the conversion of rural and natural areas into urban areas. This can lead to the loss of green spaces and vegetation, further exacerbating the UHI effect and other environmental problems, such as air and water pollution. Urban Land Cover Changes (ULCC) due to urbanization are primarily caused by the removal of vegetation cover, which affects the surface climate. When surfaces of different

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materials receive the same amount of solar radiation, the resulting temperatures vary due to differences in their heat capacity (Dissanayake et al., 2020).

Satellite remote sensing offers a cost-effective and time-saving method for conducting spatial-temporal analyses of Land Surface Temperature (LST) distribution. ERDAS Imagine and ArcMap are utilized for image processing and Geographic Information System (GIS) procedures. In this research, vegetation indices, including Normalized Difference Vegetation Index (NDVI) maps, and LULC maps, were employed to establish the correlation between LST and LULC. The main objective of this study is to assess the impact of UHI resulting from changes in LULC and LST over the past 30 years in the Kalutara district, Sri Lanka.

2 Materials and Methods

2.1 Study Area

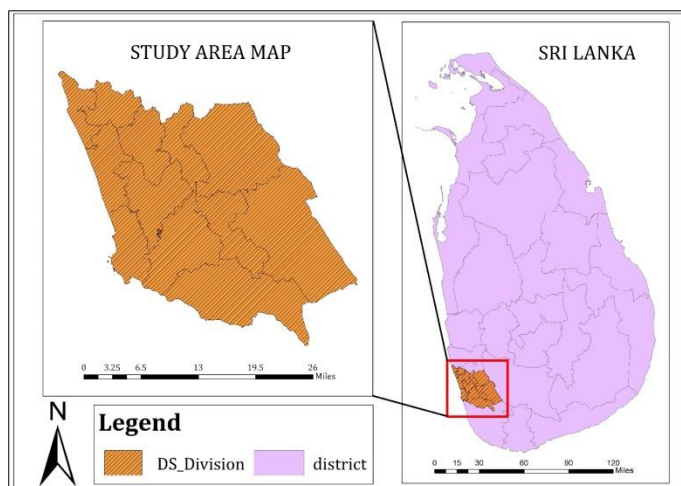


Fig. 1: Location map of the study area.

Table 1: User Queries adapted from.

Acquisition Date	Satellite	Sensor	Resolution	Band Used	Cloud Cover
22-Nov-1991	Landsat 5	Thematic Mapper (TM)	30 m for most bands, except Thermal Infrared (120 m)	Band 1 Band 2 Band 3 Band 6	30%
14-Sep-2001	Landsat 5	Thematic Mapper (TM)	30 m for most bands, except Thermal Infrared (120 m)	Band 1 Band 2 Band 3 Band 6	30%
7-Dec-2011	Landsat 7	Enhanced Thematic Mapper Plus (ETM+)	30 m for most bands, except Thermal Infrared (60 m)	Band 1 Band 2 Band 3 Band 6	30%
26-Dec-2021	Landsat 8	Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS)	30 m for most bands, except Thermal Infrared (100 m)	Band 2 Band 3 Band 4 Band 10	30%

This study focuses on the Kalutara District, situated in the Western Province of Sri Lanka, as shown in Fig. 1. The district is located at approximately latitude 6.5875° N and longitude 79.9600° E. Kalutara District features varying elevations relative to the sea level, with coastal areas resting at sea level and inland regions gradually rising a few meters above it. Specific elevations vary by location within the district. As of September 2021, the estimated population of Kalutara District was around 1,354,000 people. It's important to note that population figures are subject to change over time, so referring to the most up-to-date data is advisable. The district experiences a tropical climate characterized by warm temperatures year-round, though temperature values may vary depending on the season and specific locations within the district.

2.2 Data collection

Landsat 5, Landsat 7, and Landsat 8 satellite images were obtained from the USGS Earth Explorer (refer to Table 1), while shape files for the Kalutara District Divisional Secretarial (DS) division and Gama Niladari (GN) division were downloaded from the website of the Survey Department of Sri Lanka. Landsat images from the years 1991, 2001, 2011, and 2021 were acquired to create both the LST maps and LULC maps. To maintain a high level of accuracy in the study, images with cloud coverage consistently below 30% were selected.

2.3 Land Surface Temperature (LST)

Geometrically corrected Landsat Thematic Mapper (LTM) thermal infrared images are utilized to determine the LST, which refers to the temperature of the Earth's surface as measured from space. LST plays a crucial role in various applications such as climate studies, urban heat island analysis, and environmental assessment. Landsat 5, 7, and 8 remote sensing satellites provide valuable data for estimating LST.

Notably, Landsat 5 TM images and Landsat 7 ETM+ images have thermal infrared bands with spatial resolutions of 120 m and 60 m, respectively (Chen et al., 2006).

The calculation of LST using Landsat images involves several steps. Hence, as a first step, the Landsat satellite imagery, including the thermal infrared band, is acquired for the study area. In light of that, the calibration coefficients mentioned in the Landsat guide are applied to the raw Digital Numbers (DNs) to produce radiances. Applying the calibration factors described in the Landsat manual results in the conversion of the raw DN to radiances. The digital number of the Landsat 5-TM Thermal Infrared (TIR) band is converted to spectral radiance by equation 1 (Alshaikh, 2015).

$$\text{CVR} = 0.0056322 \times \text{DN} + 0.1238 \quad (1)$$

where CVR is the spectral radiance in $\text{Wm}^{-2} \text{sr}^{-1}$.

As the next step, the imagery undergoes preprocessing, which includes radiometric calibration, atmospheric correction, and geometric correction, ensuring accurate data. The Top of Atmosphere (TOA) brightness temperature is calculated using the thermal infrared band, representing the surface temperature along with atmospheric influences. There, atmospheric correction is performed to estimate and remove the atmospheric effects from the TOA brightness temperature, enhancing the accuracy of the results. The third step is to estimate the Land Surface Emissivity (LSE). LSE is obtained by using a comparatively straightforward method based on the Normalized Difference Vegetation Index (NDVI). The emissivity values are obtained from the NDVI using this method. Vegetated and non-vegetated areas were distinguished corresponding to the NDVI values, which were calculated from the visible (0.63–0.69 μm) and near-infrared (0.76–0.90 μm) data of TM images based on equation 2 (Sobrino et al., 2004).

$$\text{NDVI} = (\text{R}_{\text{NIR}} - \text{R}_{\text{RED}}) / (\text{R}_{\text{NIR}} + \text{R}_{\text{RED}}) \quad (2)$$

where, R_{NIR} and R_{RED} are the spectral reflectance in the TM and ETM+ red and near-infrared bands. Correspondingly, the emissivity-corrected LST are computed using the below equation 3 (Yuan and Bauer, 2007).

$$\text{LST} = \frac{T_B}{1 + \left(\frac{\lambda \sigma T_B^4}{h c \ln \epsilon} \right)} \quad (3)$$

Where λ is the effective wavelength

σ is Stefan Boltzmann constant ($1.38 \times 10^{-23} \text{ J/K}$)

h is Plank's constant ($6.626 \times 10^{-34} \text{ Js}$)

c is the velocity of light at a vacuum ($2.998 \times 10^{-8} \text{ m/s}$)

ϵ is emissivity and

T_B is at-satellite brightness temperature

2.4 Urban Heat Islands (UHIs)

Remote Sensing and GIS have been recognized as highly effective and responsive tools in urban climate research and decision support (Faisal et al., 2021). They play a crucial role in assessing, particularly for studying the UHI phenomenon in urban areas. UHI can be quantified using LST maps by comparing temperature differences between urban and non-urban regions. UHI is an occurrence in which urban areas experience higher temperatures than their surrounding rural or non-urban areas (Jafari et al., 2017). Equation 4, which calculates UHI, is as follows:

$$\text{LST} > \mu + 0.5 \times \delta \text{ Referred to UHI area} \quad (4)$$

Where μ and δ are the mean and standard deviation of temperatures in the study area, respectively.

2.5 Regression Analysis

The relationship between the percentage of urban area and LST, as well as the correlation between green area and LST values were investigated through regression analysis. Data on urban area percentages and their corresponding LST values were collected from the LST maps and LULC maps.

Percentage of Built-up areas: Surface temperature disparities between rural and urban areas are primarily attributed to the influence of building geometry on radiative fluxes (Heinl et al., 2015). Previous studies addressed heat stress by incorporating strategies such as radiant cooling, ventilation, and evaporative cooling into building and city designs. Additionally, some research has also focused on building geometry and shading (Sari, 2021; Tavakoli et al., 2022).

Percentage of Green areas: Previous studies have frequently employed the NDVI to examine correlations between temperature and vegetation (Rhew et al., 2011). Several studies have been conducted on urban green space at various dimensions such as ranging from parks to individual rooftops (Addas, 2023; Matos Silva et al., 2023).

2.6 Methodology Flow Chart

As depicted in Fig. 2, the analysis was conducted systematically throughout the study area. Landsat imagery spanning from 1991 to 2021 was employed to generate maps of LULC, LST, and NDVI. The relationship between the percentage of urban area and LST, as well as the relationship between green area and LST, were examined through regression analysis. Subsequently, UHI intensity threshold values were calculated based on LST. Finally, the study identified UHI occurrences in the study area and elucidated the major impacts associated with these areas.

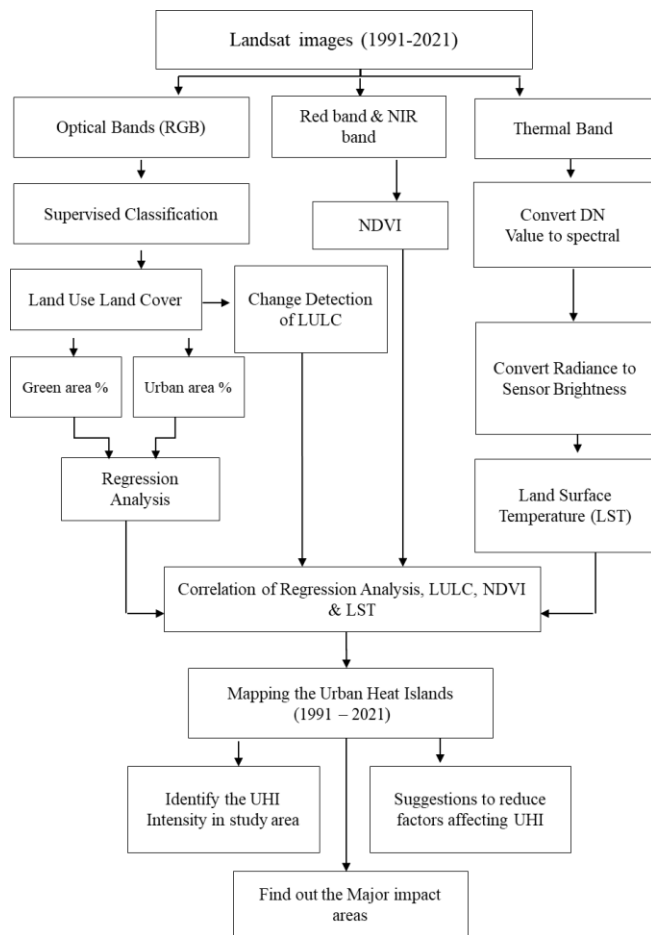


Fig. 2: Flow chart of methodology.

3 Results and Discussion

3.1 Changes of LST Pattern

LST plays a crucial role in climate studies, UHI analysis, and environmental assessments. Landsat satellites serve as valuable sources of data for estimating LST. This process typically entails acquiring imagery, performing preprocessing, and calculating the Top of Atmosphere (TOA) brightness temperature. These TOA values were calculated by using 'Raster Calculator' tool in the GIS environment. Using these methods, LST maps were generated to track changes in Land Surface Temperature from 1991 to 2021 as shown in Fig. 3.

The 1991 LST map of the Kalutara district revealed a high-temperature zone on the western side of the study area. These areas consistently exhibited higher temperatures compared to other regions. In 2001, the high-temperature areas expanded slightly, particularly toward the northern part of the study area. The red areas on the map increased compared to 1991, indicating a temperature rise beyond the previously identified zones. By 2011, temperatures in the Kalutara district continued to rise, with the map highlighting a middle range of temperature increase in yellow—an area not considered a high-temperature zone in 1991. The Kalutara district experienced a significant temperature increase compared to previous decades, with the western and northern sides of the study area being particularly at risk of high temperatures. In an overall assessment, most of the area now exhibits high temperatures, reflecting the widespread and intensified impact of rising temperatures throughout the district.

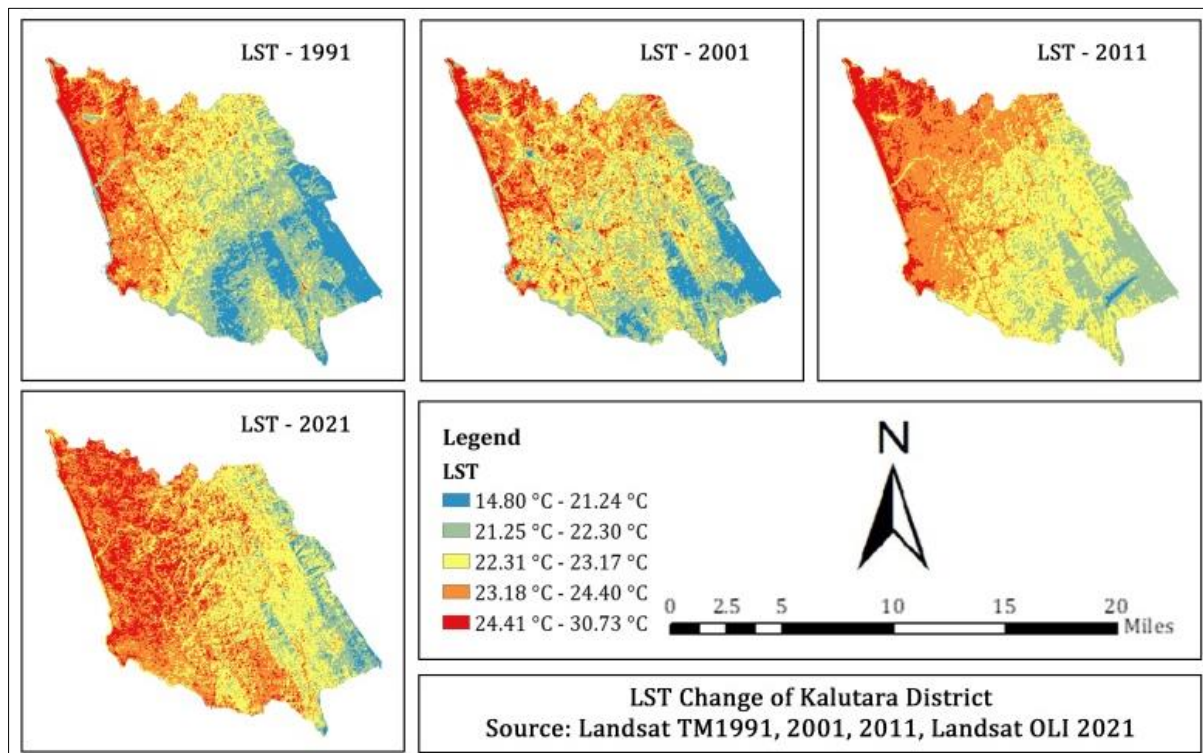


Fig. 3: Land Surface Temperatures (LST) maps for the study area.

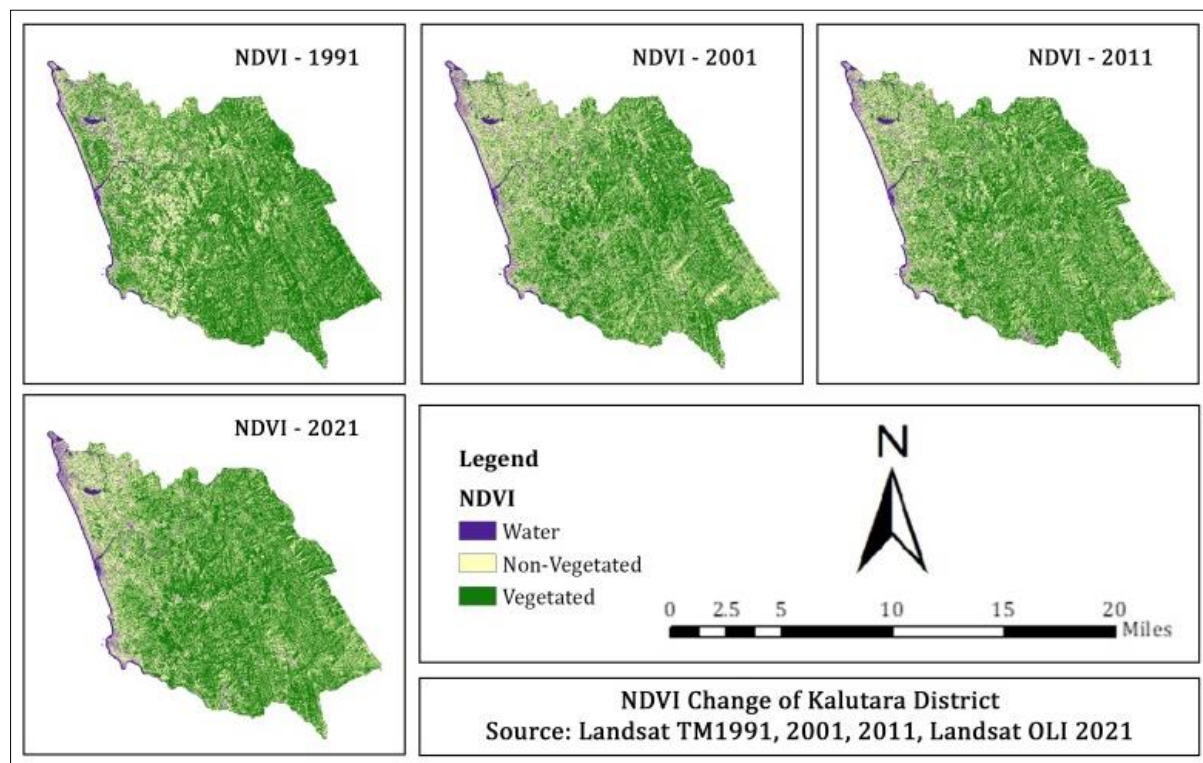


Fig. 4: NDVI maps for the study area.

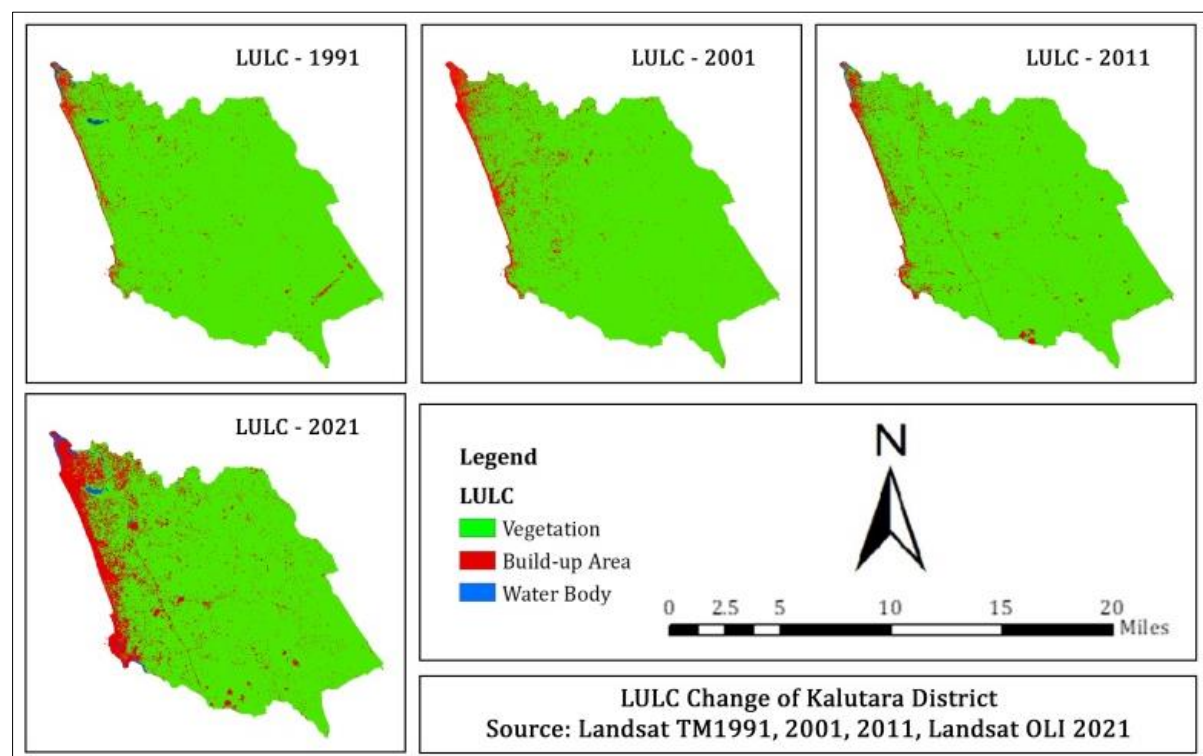


Fig. 5: LULC maps for the study area.

3.2 Changes of Vegetation Cover

Due to uncontrolled population growth, vegetation areas are gradually decreasing without any control. Image subsets were consistently extracted for the study area in

each satellite image. NDVI is calculated using equation 2, and was then employed to delineate the vegetation area. NDVI maps were generated to assess changes in vegetation cover in each decade from 1991 to 2021, and the corresponding maps are shown in Fig. 4.

The NDVI map for 1991 revealed that the green area, representing vegetation coverage, was relatively higher compared to subsequent years. However, even at this stage, the high-temperature areas (as depicted in Fig. 3) exhibited a noticeable decrease in green coverage, indicating a correlation between high temperatures and low vegetation density. The high NDVI values in 1991 indicate vigorous growth and productivity of vegetation during that time.

In the 2001 NDVI map, the trend of decreasing green coverage within high-temperature areas continued. The expansion of high-temperature zones towards the north was accompanied by a further reduction in the green area, strengthening the observed relationship between high temperatures and diminished vegetation.

In 2011, it can be observed that the green areas representing high NDVI values experienced a significant reduction in extent and intensity. This decline in NDVI suggests a decrease in vegetation vigor or density during the period between 2001 and 2011.

The NDVI maps in 2021 highlighted a significant decrease in green coverage across the Kalutara district, particularly within the high-temperature zones. The expanding high-temperature areas observed in Fig. 3 were accompanied by a corresponding decline in vegetation density, reinforcing the relationship between high temperatures and low green coverage.

3.3 Change Detection of Land Use Land Cover

The study involved the utilization of Landsat 8, 7, and 5 satellite images to perform LULC classification. To train the classifier, representative training samples were collected, encompassing various land cover classes present in the study area. These samples were meticulously selected to accurately represent each class of interest. Ground truth data and existing land cover maps were utilized to guide the sample collection process. The LULC maps were created to determine the change in Land Cover in each decade from 1991-2021 and the relevant maps are shown in Fig. 5. The land cover classes identified included urban areas, vegetation lands and water bodies.

In the year 1991, a significant expanse of green areas is depicted, indicating the presence of abundant vegetation cover. The landscape consists of primarily forests, grasslands, and agricultural fields. Urban areas are relatively limited, with minimal human settlement and infrastructure encroachment.

As seen in the LULC map in 2001, there is a visible decrease in green areas compared to 1991, suggesting the conversion of natural vegetation to other land uses. The expansion of agricultural land, urbanization, and the establishment of human settlements becomes more apparent. The increasing presence of built-up areas signifies the encroachment of human activities into previously vegetated regions. The 2011 LULC map reveals a clear trend of increasing urban areas and decreasing green areas. The expansion of urbanization, primarily influenced by main roads, railway lines, and highways, is the main factor behind this change. In the 2021 LULC map, notable changes are observed compared to previous years, with a

significant increase in urban areas and a corresponding decrease in green areas.

The extent of each land cover class was quantified for each time period studied, as presented in Table 2, showcasing the LULC area in square kilometers for each year.

Table 2: Changes in the land use land cover in each decade

Land Use Land Cover	1991 – 2001 (Km ²)	2001 – 2011 (Km ²)	2011 – 2021 (Km ²)
Urban	+121.87	+59.94	+60.94
Vegetation	-131.62	-60.94	-158.50
Water body	-4.38	-0.63	-0.51

The urban area increased by 121.87 km² during the period from 1991 to 2001, followed by an additional increase of 59.94 km² from 2001 to 2011, and a further increase of 60.94 km² from 2011 to 2021. The vegetation area witnessed a decrease of 131.62 km² during the 1991-2001 period. This decline continued with a reduction of 60.94 km² from 2001 to 2011 and a further decrease of 158.50 km² from 2011 to 2021. The area of water-bodies experienced a decline of 4.38 km² from 1991 to 2001, followed by a decrease of 0.63 km² from 2001 to 2011, and a slight decrease of 0.51 km² from 2011 to 2021.

3.4 Regression Analysis

The study examined the relationship between the percentage of urban area and LST, and the green area with LST using regression analysis. Data were collected from LST maps and LULC maps. A linear regression model was applied, and the coefficient of determination (R²) was analyzed to determine the proportion of variation in LST explained by the percentage of urban area.

Fig. 6 displays separate graphs of percentages of green area and urban area for the study area, obtained from the attribute tables of the LULC maps for each year.

3.5 Interpretation of Urban Heat Island Intensity

For examining the spatial and temporal distribution of LST, satellite remote sensing is an ideal, cost-effective, and time-saving technology. To implement UHI mitigation strategies, it is crucial to understand the distribution of LST in urban areas and identify locations with unusually high temperatures. A closer examination of the UHI maps in the study area reveals intriguing findings. Consequently, it can be concluded that the UHI pattern aligns with the urban land use pattern in the study area.

For each image, the mean LST values plus half of the standard deviation were calculated and used as a threshold. Temperatures below this threshold were classified as non-UHI zones. The UHI threshold values, as determined by the equation 4, are as follows: 23.43 °C for 1991, 23.97 °C for 2001, 25.84 °C for 2011, and 27.64 °C for 2021, as indicated in Table 3.

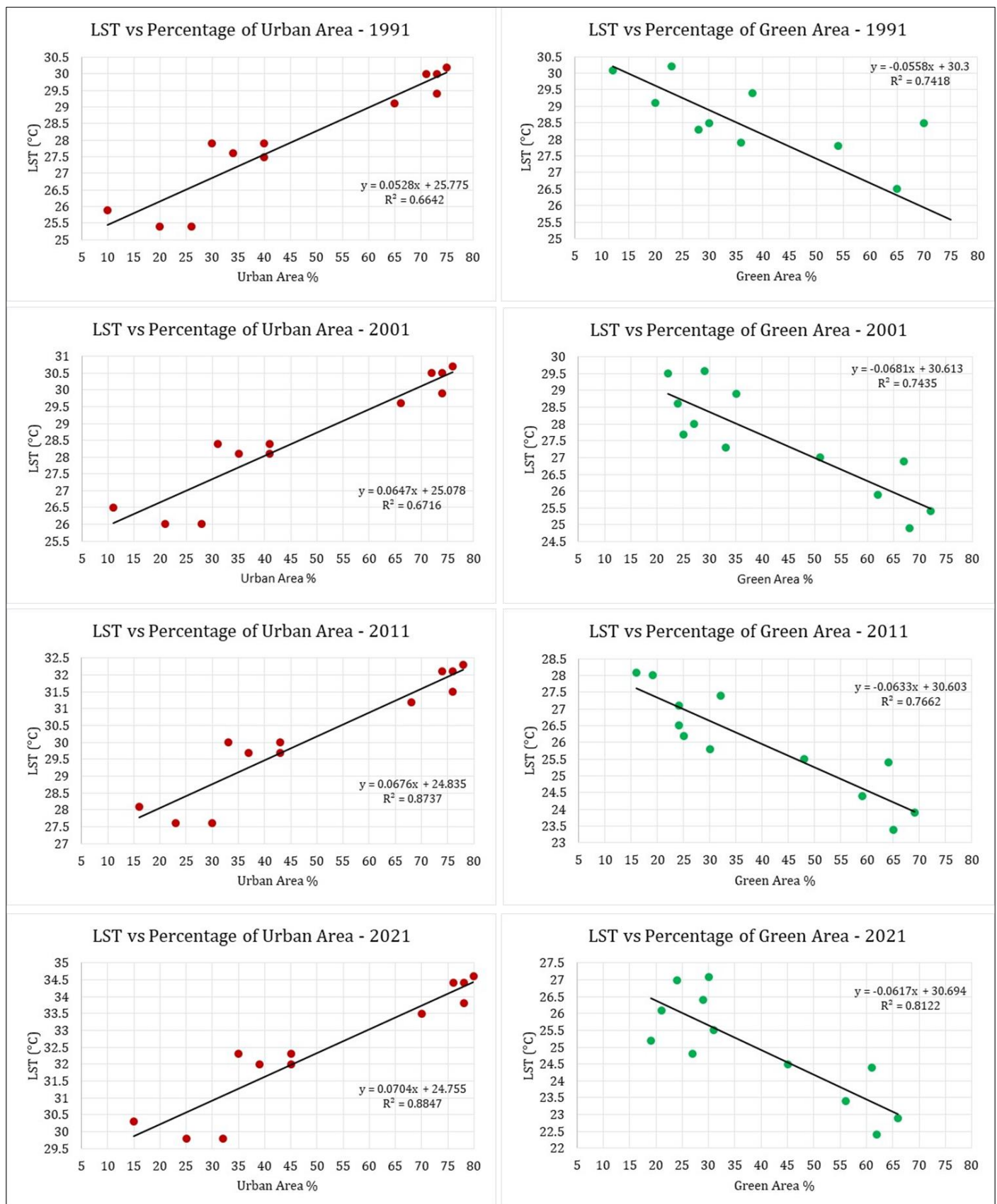
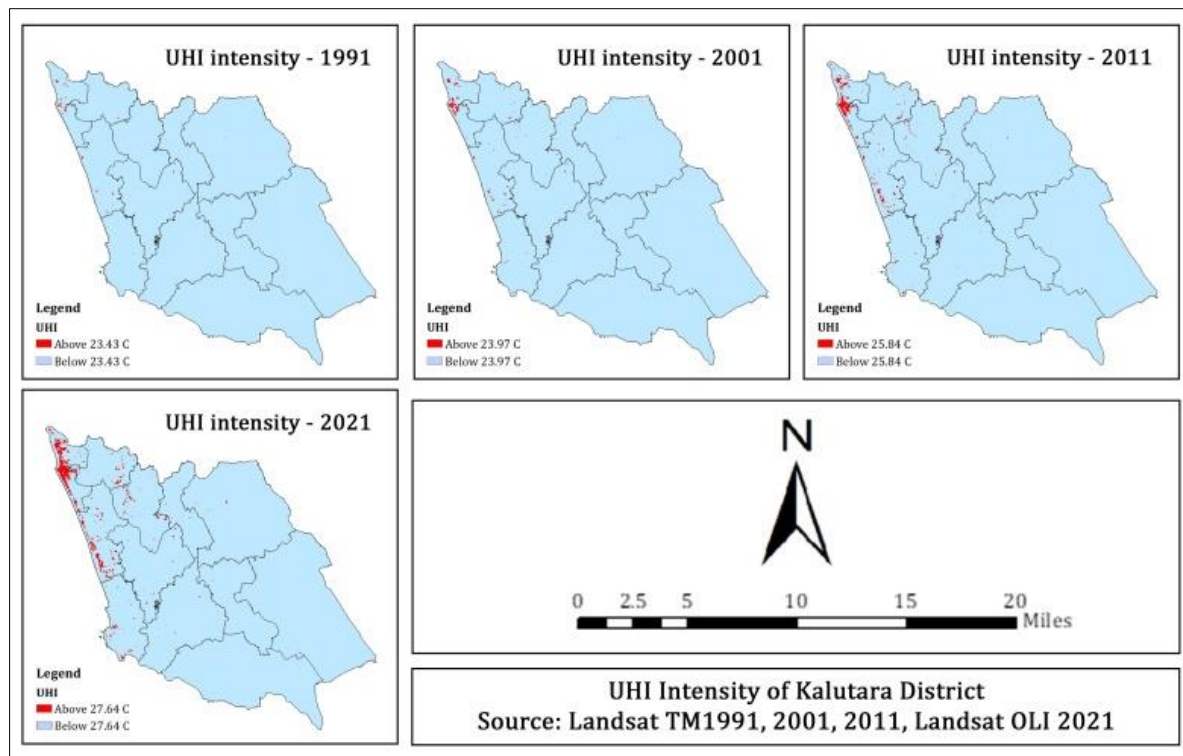


Fig. 6: Left: relationship between the LST and percentage of built-up areas, and right: relationship between the LST and green areas in Kalutara District, Sri Lanka.

Table 3: LST statistics based on Landsat images.

Year	Max Temp. (°C)	Min Temp. (°C)	Mean Temp. (°C)	St. Dev.	LST(°C)
1991	28.13	16.42	22.28	2.3	23.43
2001	29.73	14.80	22.27	3.4	23.97
2011	30.53	18.74	24.64	2.4	25.84
2021	31.35	21.22	26.29	2.7	27.64

**Fig. 7:** UHI intensity and UHI zones.

Calculations of UHI based on the relationship described in equation 4 demonstrated that the studied area experienced varying UHI intensities over the years under investigation. Specifically, the UHI intensity was 3.76 °C in 1991, 4.55 °C in 2001, 4.59 °C in 2011, and 4.96 °C in 2021 (see Table 4).

Table 4: Calculation of UHI intensity from LST based on LANDSAT images.

Year	Urban LST Mean (°C)	Green LST Mean (°C)	UHI Intensity (°C)
1991	27.96	24.20	3.76
2001	28.72	24.17	4.55
2011	29.61	25.02	4.59
2021	30.27	25.31	4.96

Table 3 presents the temperature difference between urban (built-up regions) and vegetated lands in the focus

area. This difference in mean temperature (μ) between urban and cultivated lands serves as a measure of UHI. The results indicate a consistent increase in UHI intensity as a general trend, with values exceeding 4 °C over the past 30 years (from 1991 to 2021), compared to the initial year of 1991 (3.76 °C). To determine the Urban LST, temperature values were obtained from pixel samples in the LST map taken from several urban area locations.

The maps in Fig. 7 clearly illustrate the distribution of UHIs, particularly in coastal cities. When comparing different years, it becomes evident that the extent of UHI has significantly increased over time, with the highest expansion observed in 2011 and 2021. This indicates a rising trend in UHIs within the region, highlighting the growing impact of urbanization and the associated heat-related challenges. Analyzing the UHI maps for different time periods enables us to comprehend the spatial and temporal dynamics of heat islands, providing valuable insights for future urban planning and climate mitigation strategies.

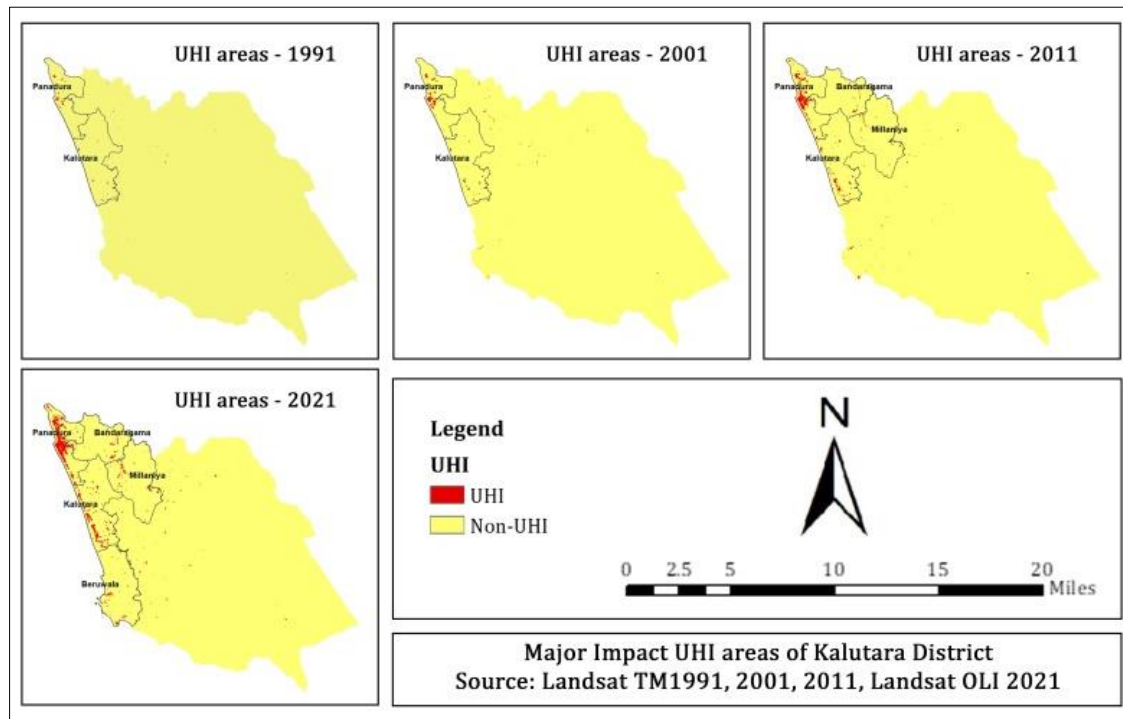


Fig. 8: Major impact UHI zones

3.6 Major Impact UHI Areas

The analysis of LST and LULC maps reveals a troubling trend characterized by diminishing green areas and expanding urbanization. The simultaneous increase in LST values signifies the presence of UHI effects in specific areas, as depicted in Fig. 8.

In 1991, the UHI effect in the Kalutara district was relatively limited with only two DS divisions, namely Kalutara and Panadura, displaying discernible UHI patterns. However, by 2021, the UHI effect had significantly intensified, impacting a larger area within the Kalutara district. The DS divisions affected by UHI now included Kalutara, Panadura, Millaniya, Bandaragama, and Beruwala. The spread of UHI in 2021 indicated a considerable expansion of urban areas and their associated heat island effects across the district. Fig. 8 marks the most extensive UHI presence observed over the four-decade period.

The results of the UHI spreading have been examined and mapped, revealing significant impacts on various areas. The coastal area emerged as the primary affected region, characterized by a higher concentration of buildings and main roads within its boundaries. The maps clearly illustrate that the major affected areas are the Panadura and Kalutara DS divisions.

3.7 Factors Influencing the Spread of UHIs

By utilizing LST maps and LULC maps for the years 1991, 2001, 2011, and 2021, this study investigates the impact of vegetation cover loss and the expansion of urban areas on the prevalence of UHIs. Additionally, it examines the decline in the number of water features and their correlation with rising surface temperatures. The findings underscore the significance of water features in mitigating

the effects of UHIs and provide valuable insights for effective urban planning and strategies to mitigate heat islands.

Based on the study's findings, the following recommendations are proposed for mitigating UHI effects in the Kalutara district:

- Implement urban greening initiatives to increase vegetation cover and leverage the cooling effect of plants.
- Integrate water features, such as lakes, ponds, and canals, into urban planning to enhance evaporative cooling and serve as heat sinks.
- Recognize that the presence of high-rise buildings in coastal areas presents a unique challenge for UHI mitigation. While sea winds offer natural cooling potential, their effectiveness is diminished by tall structures. Addressing this challenge necessitates careful consideration of urban design, planning and building regulations, and strategic interventions.

4 Conclusion

The results reveal a dramatic expansion of the built-up class in the Kalutara district at the expense of cultivated land, leading to significant changes in the study area. The analysis of the UHI indicates a growing influence of urbanization on local temperatures. UHI effects, which were initially confined to urban centers such as Kalutara and Panadura DS divisions in 1991, gradually spread to other DS divisions, including Beruwala, Millaniya, and Bandaragama, by 2021. Moreover, the UHI threshold values have increased over time, indicating a substantial rise in urban temperatures.

These findings clearly demonstrate that the Kalutara district has undergone significant environmental changes, characterized by rising temperatures, reduced vegetation density, and the expansion of urban areas. This underscores the pressing need for sustainable land management practices and effective urban planning strategies. Preserving green areas, promoting afforestation, and implementing measures to mitigate UHI effects are crucial steps toward maintaining a balanced and healthy environment within the district. The major findings from this study are valuable for informing policies that promote more sustainable urban development in cities. To improve the classification accuracy of LULC, for future research it is suggested to use high-resolution satellite imagery and advanced machine learning algorithms such as random forests, support vector machines, or convolutional neural networks to enhance the spatial detail and enable better discrimination between land cover classes. Furthermore, it is recommended to identify potential areas for further research that could build upon the findings of this study. For instance, conducting more detailed examinations of various land cover classes, such as impervious surfaces, may provide valuable insights into their influence on LST and UHI effects.

Acknowledgement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author Contributions

Conceptualization, methodology, analysis, writing - original draft preparation, T.K.C.N.T., .D.S.M., L.K.K.Y., and writing - review and editing, T.K.C.N.T., .D.S.M.. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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