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Spatio-Temporal Analysis of Urban Heat Island and Land Use/Land Cover Dynamics Using Remote Sensing and GIS: A Case Study of Varanasi, India

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Abstract: ***Urban Heat Island (UHI) is among the most significant aspects of rapid urbanization and unplanned land use and development in developing cities. In the present study, spatio-temporal variation of intensity of Urban Heat Island (UHI) and its correlation with land use and land cover (LULC) change in Varanasi have been analyzed with the help of a Remote Sensing (RS) and Geographic Information System (GIS) techniques. Multi-temporal Landsat satellite imagery (2005, 2015, and 2025) were used to analyse the changes in Land Surface Temperature (LST), vegetation cover, built-up areas, moisture conditions and barren land distribution in the study area. Various spectral indices such as Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), Normalized Difference Built-up Index (NDBI) and Normalized Difference Bareness Index (NDBaI) were calculated to assess the environmental transformation and thermal characteristics of urban areas. The findings showed that there was a substantial increase in built-up surfaces and barren land with a decrease in the amount of vegetation cover and moisture-rich areas between the years 2001 and 2018. Spatial analysis indicated that comparatively higher LST values were found in urban dense areas while lower LST values were found in areas with vegetation cover and close to the River Ganga. The negative relationship between LST and NDVI/NDWI, along with positive relationships between LST and NDBI/NDBaI was found using correlation analysis, which suggests that built-up and exposed surfaces play a significant role in the creation of UHI. The results indicate that rapid urbanization has affected the environment and the need for sustainable urban planning, afforestation in urban areas, protection of water bodies and infrastructure that can adapt to climate change in order to reduce the effects of the Urban Heat Island in rapidly growing cities and make the urban environment more sustainable.***
Keywords: City; Land use pattern; Land surface temperature; Sustainability; Remote sensing.

I. INTRODUCTION

Urbanization is one of the most pronounced factors of environmental change in the twenty first century, bringing about significant changes to the natural environment and the local climate. Urban development, with its associated population growth, industrialization, and infrastructure development, has been the driver for more rapid rates of change in vegetated and agricultural areas to impervious built-up surfaces. Changes in land use and land cover (LULC) affect the surface energy balance, decrease evapotranspiration, increase heat absorption, and thus, enhance the Urban Heat Island (UHI) effect. The UHI phenomenon is gaining increasing significance as an environmental issue that poses challenges for ecosystem services, human health, energy and urban climate resilience. Land Surface Temperature (LST) is one of the most well-known parameters to determine urban thermal environment. In contrast to air temperature, LST directly reflects the thermal nature of the Earth's surface and offers useful insights into the land cover-vegetation-moisture-urban surfaces relationship. The growing amount of freely available and accessible satellite images has allowed researchers to consistently track long-term changes in temperature and urbanization in space and time. As a result, Remote Sensing (RS) and Geographic Information Systems (GIS) have become essential tools to study the city's environmental dynamics and to guide urban planning decisions based on evidence Chatrabhuj and Meshram (2023).

The Landsat series is one of the longest continuous Earth observation satellite series, and is a good choice to perform multi-temporal analysis of urban growth and thermal changes. The thermal infrared bands present in the Landsat data can be used to retrieve Land Surface Temperature, and the multi-spectral bands can be used to calculate spectral indices like Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), Normalized Difference Built-up Index (NDBI), and Normalized Difference Bareness Index (NDBaI). The indices quantify vegetation health, surface moisture, impervious surfaces and barren land, which enable a comprehensive assessment of environmental changes related to urbanization.

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In the past two decades, India has undergone a rapid urbanization, leading to significant changes in land resources in a number of metropolitan and medium-sized cities. Varanasi, the oldest city world in continuous occupation is considerably expanded due to population growth, tourism, transport, educational institutions and commercial activities. Built-up development of vegetation, open spaces and agricultural land has changed the thermal environment of the city and led to the rise in the number and severity of the heat stress events.

Although, a number of studies have been carried out to examine the urban expansion and UHI issues of Indian cities, the monitoring activities in Varanasi city with the latest satellite observations are still limited in this city as significant urban development has been observed after the year 2015. In the present study, the spatio-temporal evolution of the intensity of the Urban Heat Island and the changes in the land use/land cover of Varanasi were analysed using multi-temporal Landsat satellite images from 2005, 2015, and 2025. The thermal infrared data was used to estimate Land Surface Temperature (LST), and the derived indices: NDVI, NDWI, NDBI, and NDBaI were used to study the environmental parameters affecting the urban thermal behavior. Correlation analysis was performed to evaluate the relationships between thermal conditions and spectral indices. The results offer valuable insights into urban environmental change and contribute to sustainable urban planning, urban adaptation to climate change and the development of green infrastructures in areas undergoing rapid urbanization.

II. LITERATURE REVIEW

A very brief overview of the theory behind UHI and urban development. Very basic theory of UHI and urbanization. This has drastically changed the thermal behavior of cities around the world due to the increased rate of urbanisation. Impervious surfaces like concrete, asphalt, and buildings alter the surface energy balance and are a major factor in the development of Urban Heat Island. Initial research confirmed that urban areas consistently record an above average temperature as compared to their surrounding rural areas, attributed to the physical effect of less evapotranspiration, more heat storage, and anthropogenic heat output. With the pioneering work of Voogt and Oke (2003), thermal remote-sensing is one of the most reliable techniques for assessing urban climate and used to detect spatial variations in land surface temperature. They have highlighted the importance of satellite-based thermal data in urban planning, climate adaptation and environmental monitoring.

Likewise, Weng (2009) showed how multi-temporal Landsat scene was effective for long-term monitoring of urban thermal environment, and the need to combine thermal and land use remote sensing analysis. Uncontrolled urban expansion has also been established by recent investigations to significantly contribute to thermal stress. By studying various Indian metropolitan cities, Shahfahad et al. (2020) concluded that built-up density has a significant positive impact on Land Surface Temperature (LST) and vegetation has a cooling effect in the study area. Similarly, Mihalache and Dumitrașcu (2026) found that urban sprawl and loss of vegetation cover in urban areas exacerbated Urban Heat Island in the fast-growing urban areas. This course covers the use of remote sensing and Geographic Information Systems (GIS) in monitoring Land Use/Land Cover (LULC).

The monitoring of land uses change at various spatial and temporal scales has become an indispensable technology using Remote Sensing and Geographic Information Systems. Satellite observations are a powerful, cost-effective and efficient tool to detect urban expansion, vegetation degradation, loss of wetlands and transformation of environments, with information that is reliable. The Landsat satellite program has been widely used due to its long time series and moderate spatial resolution. Rawat and Kumar (2015) proved that Landsat image can be used for accurate classification of LULC Chatrabhuj and Meshram (2024) and change detection in Indian context. Likewise, Shekar and Mathew (2023) used Landsat data with high classification accuracy and effective detection of environmental changes to analyze land use changes at the watershed level. The usefulness of multi-temporal satellite observations has also been confirmed by several investigations worldwide. Finally, Meshesha et al. (2016) recorded significant land cover alterations in Ethiopia during a 30-year period, and Tesfay et al. (2025) pointed out the rapid pace of peri-urban land use alteration across the Global South.

These studies show that Remote Sensing and GIS can be powerful instruments for understanding and analyzing the urban development and environmental sustainability trends over time. The multispectral satellite-derived spectral indices can be used to obtain quantitative data for vegetation, moisture, built-up areas, and bare surfaces. Of these, NDVI is still one of the most popular vegetation health and density indicators. Many other studies have consistently found high negative correlation between NDVI and LST, as vegetation has cooling effect and minimizes heat storage. Chatrabhuj and Meshram (2025) showed that the surface temperature is significantly inversely correlated with vegetation density and hence the significance of urban green spaces on UHI mitigation. Likewise, Yuan and Bauer (2007) compared vegetation and impervious surface indicators and found that the built-up surfaces were good predictors of rising urban temperatures. Normalized Difference Built-up Index (NDBI) is one of the most popular and standard methods for urban impervious surface detection, which generally has higher thermal properties.

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NDWI, on the other hand, was used to detect moisture-rich surfaces which have a capacity for evaporative cooling, and NDBaI was useful for detecting barren areas linked to high surface temperature Chatrabhuj and Meshram, (2024). The combination of these indices and LST can help a comprehensive evaluation of the urban environment and be a valuable aid for climate-sensitive urban planning Karimi et al., (2024).

A. Research Gap

Many studies have examined the trends of UHI intensity and land use changes in various parts of the world, but there are some gaps in research. While a large number of earlier studies were confined to the large metropolitan cities, the medium sized historic cities like Varanasi are comparatively less studied, despite being witnessing very fast urban growth. In addition, a few previous studies have assessed only one Land Surface Temperature or single spectral indices without considering multiple environmental indicators in a single analytical framework.

In the present study, these limitations are overcome by studying and analyzing all four indices (LST, NDVI, NDWI, NDBI and NDBaI) with multi-temporal Landsat imagery over a 20-year period (2005–2025). By combining the thermal analysis with the spectral indices, a comprehensive picture of urban expansion, environmental degradation and thermal behaviour can be obtained. The results help inform urban planning that is more resilient to climate change by pinpointing the most vulnerable areas for the environment and sustainable land management.

III. MATERIALS AND METHODS

A. Methodology

The generated LST maps were used to identify thermal hotspots and Urban Heat Island intensity across the city, as shown in Figure 1

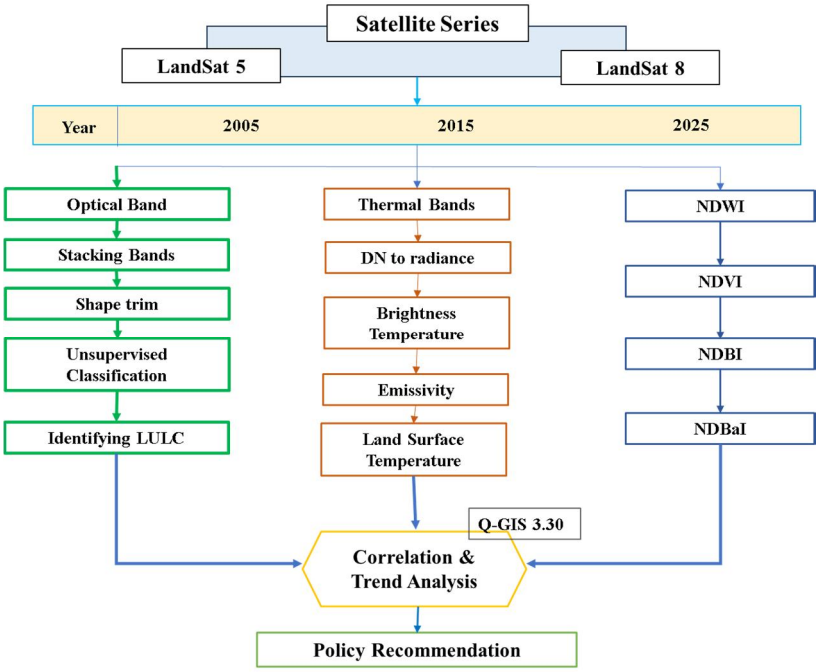


Figure 1 Flowchart

B. Study Area

Varanasi, one of the oldest continuously inhabited cities in the world, is situated in the eastern part of Uttar Pradesh, India, along the western bank of the River Ganga. Geographically, the city extends approximately between 25°14′N–25°23′N latitude and 82°56′E–83°03′E longitude, with an average elevation of nearly 80 m above mean sea level, as shown in Figure 2

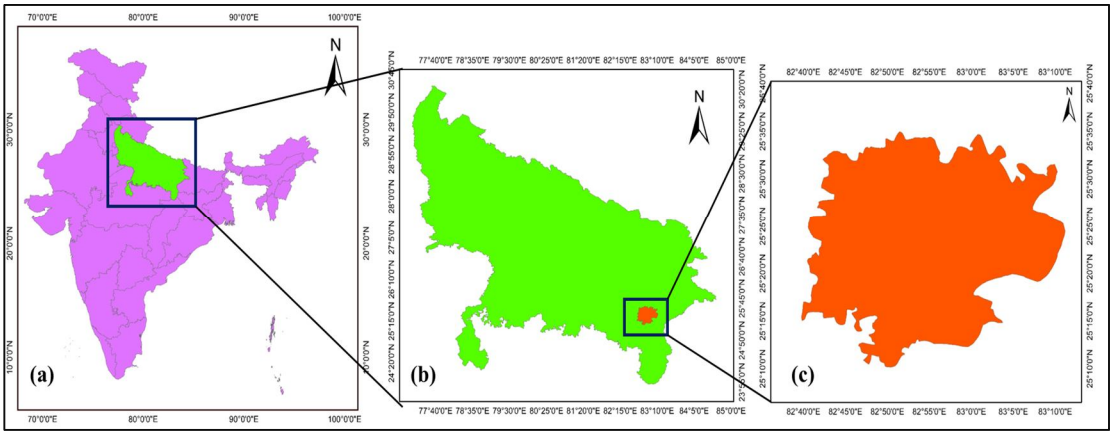


Figure 2 (a) Map of India (b) Map of Uttar Pradesh (c) Map of Varanasi

C. Data Sources

Multi-temporal Landsat satellite imagery was employed to investigate the spatial and temporal evolution of land use/land cover and Urban Heat Island characteristics during 2005–2025. Landsat-5 Thematic Mapper (TM) imagery was utilized for 2005, whereas Landsat-8 Operational Land Imager/Thermal Infrared Sensor (OLI/TIRS) imagery was used for 2015 and 2025, as given in Table 1

Table 1 Source of satellite images

Year	Satellite	Sensor	Resolution	Cloud Cover
2005	Landsat 5	TM	30 m	<5%
2015	Landsat 8	OLI/TIRS	30 m	<5%
2025	Landsat 8	OLI/TIRS	30 m	<5%

Source: USGS Earth Explorer (https://earthexplorer.usgs.gov)

Additional spatial datasets, including administrative boundaries, Google Earth imagery, and topographic information, were utilized for image interpretation, verification, and preparation of thematic maps.

IV. RESULTS AND DISCUSSION

A. Land Use/Land Cover Dynamics

The multi-temporal land use/land cover (LULC) analysis revealed substantial changes in the spatial distribution of land cover classes in Varanasi between 2005 and 2025 as given in Figure 3. Four dominant land use classes were identified, namely built-up area, vegetation, water bodies, and barren land. The observed changes reflect the rapid urbanization and infrastructural expansion that have occurred over the past two decades.

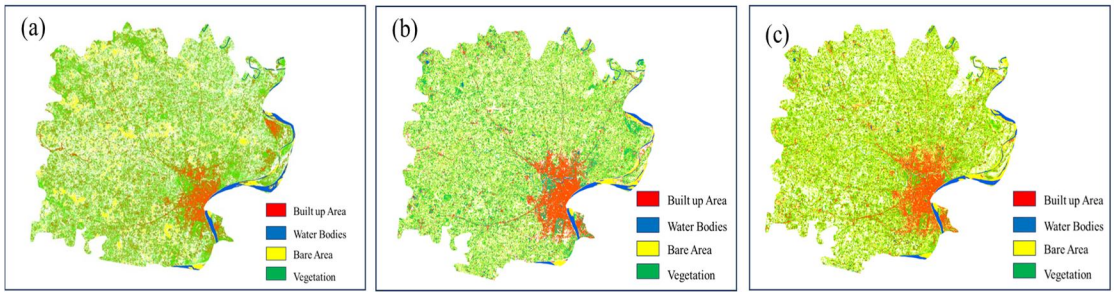


Figure 3 Land use pattern of Varanasi (a) 2005 (b) 2015 (c) 2025

The LULC analysis demonstrates that rapid urbanization and infrastructural development have significantly altered the landscape pattern of Varanasi between 2005 and 2025. Expansion of built-up surfaces and reduction in vegetation cover have contributed to increasing environmental stress, land degradation, and intensification of Urban Heat Island (UHI) conditions within the urban environment.

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B. Land Use Change Detection

The change detection analysis further quantified the magnitude of land transformation between 2005 and 2025, as in Figure 4. Comparison of classified images demonstrated that urban expansion occurred predominantly at the expense of vegetation and open land.

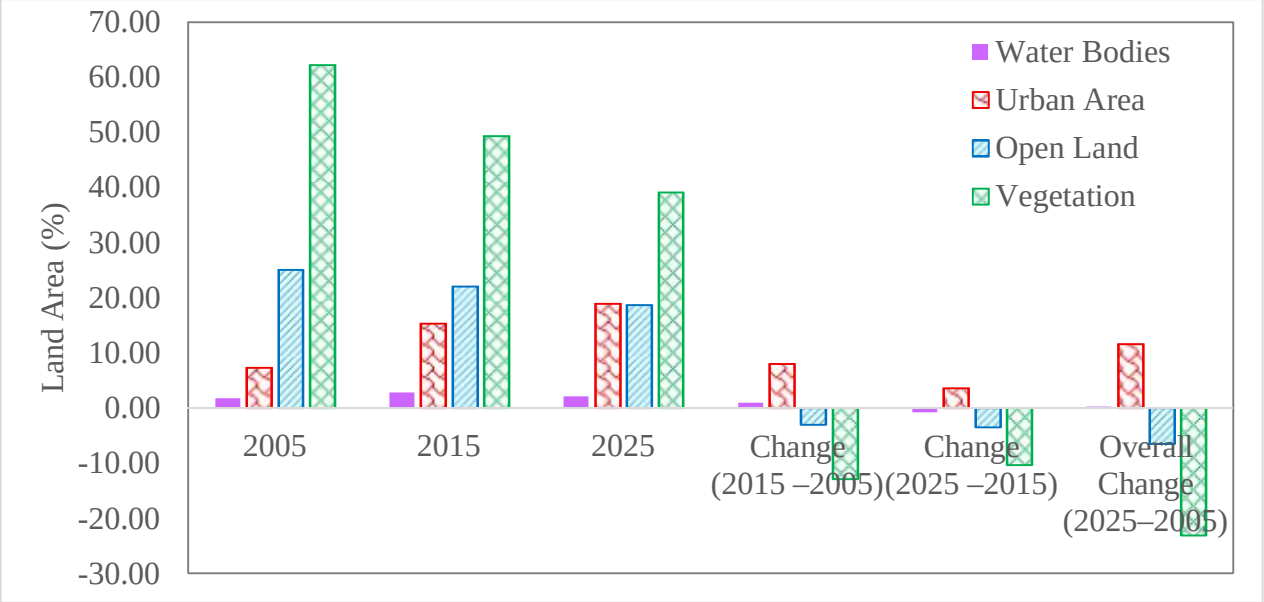


Figure 4 Change detection

Built-up land showed the greatest growth, due to the city's fast demographic and economic growth. Growth was especially strong in the new transportation corridors and suburban areas. The highest loss was in vegetation, reflecting ongoing erosion of natural surfaces to impervious infrastructure. The reduction of vegetation is significant in terms of the environment as vegetation serves as a natural cooling mechanism through evapotranspiration. With decreased tree cover, latent heat flux decreases and sensible heat increases, which leads to higher land surface temperatures. The spatial distribution of land surface temperature has been illustrated.

C. Spatial Distribution of Land Surface Temperature

Land Surface Temperature (LST) maps derived from Landsat thermal imagery revealed significant spatial and temporal variation across Varanasi during the study period, as given in Figure 5. Thermal distribution clearly demonstrates increasing surface temperatures associated with urban expansion.

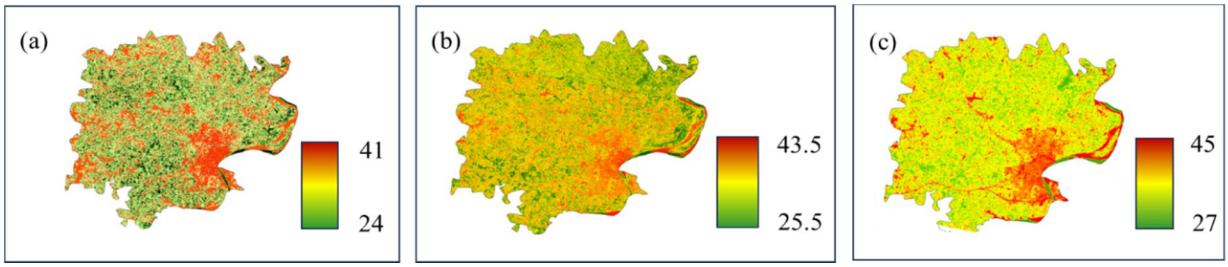


Figure 5 Final LST of Varanasi (a) 2005 (b) 2015 (c) 2025

By 2025, LST values further increased from 27°C to 45°C, reflecting intensified Urban Heat Island conditions across the study area. High-temperature zones became more widespread due to continuous reduction in vegetation cover and expansion of concrete and asphalt surfaces. In contrast, lower temperatures remained concentrated near water bodies and green spaces because of their cooling effects.

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D. Normalized Difference Vegetation Index (NDVI)

Spatial analysis of NDVI indicated a continuous decline in vegetation density during the twenty-year study period, as given in Figure 6. Higher NDVI values were primarily associated with agricultural land, urban parks, forest patches, and riparian vegetation along the River Ganga.

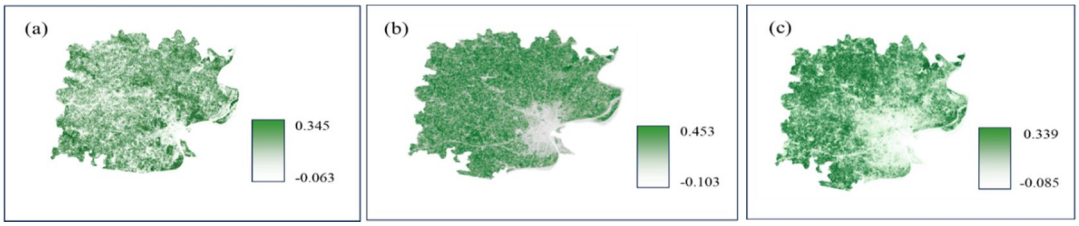


Figure 6 NDVI of Varanasi (a) 2005 (b) 2015 (c) 2025

Areas exhibiting low NDVI values corresponded predominantly to built-up surfaces and barren land. Between 2005 and 2025, vegetation loss became increasingly evident around expanding residential neighborhoods and commercial developments. Reduction in NDVI is directly associated with increasing urban temperature because vegetation facilitates evapotranspiration, enhances surface moisture, and provides shading. Consequently, areas characterized by high NDVI generally exhibited comparatively lower Land Surface Temperature.

E. Normalized Difference Water Index (NDWI)

The NDWI analysis illustrated the spatial distribution of water bodies and surface moisture across Varanasi, as given in Figure 7. High NDWI values were observed along the River Ganga and in areas containing ponds, wetlands, and moisture-rich surfaces.

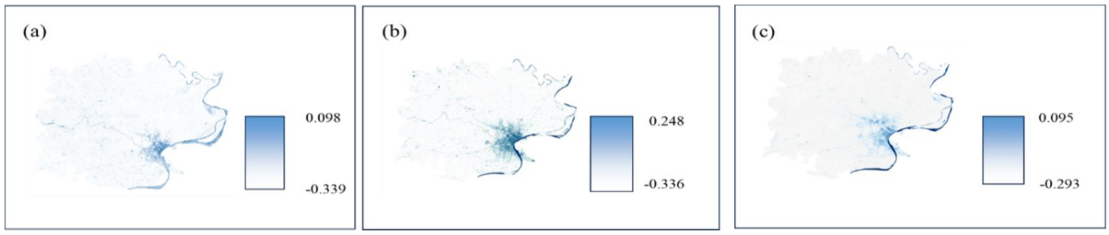


Figure 7 NDWI of Varanasi (a) 2005 (b) 2015 (c) 2025

Comparison of multi-temporal images indicated a gradual decline in moisture-rich regions, particularly in peripheral urban areas where increasing construction activities have reduced natural drainage systems and water retention capacity. Lower NDWI values corresponded closely with higher Land Surface Temperature, indicating that reduction in surface moisture contributes significantly to thermal intensification. Water bodies act as natural temperature regulators through evaporation, thereby reducing thermal stress in surrounding areas.

F. Normalized Difference Built-up Index (NDBI)

The Normalized Difference Built-up Index (NDBI) was employed to characterize the spatial distribution and temporal expansion of impervious surfaces in Varanasi. Figure 8 illustrates the progressive increase in NDBI values during 2005–2025, indicating continuous urban growth and infrastructure development.

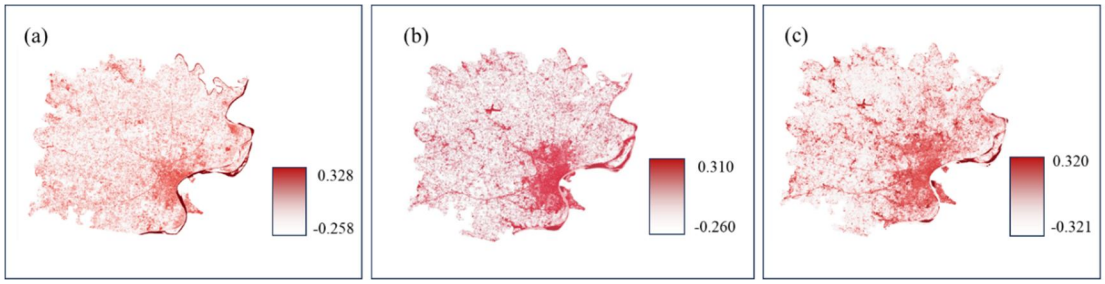


Figure 8 NDBI of Varanasi (a) 2005 (b) 2015 (c) 2025

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By 2025, NDBI values ranged from −0.321 to 0.320, demonstrating further intensification of impervious surfaces and spatial expansion of urbanized areas across the city. The increasing dominance of higher NDBI zones reflects continuous conversion of agricultural land, vegetation cover, and open spaces into concrete structures, roads, and commercial establishments. The temporal increase in NDBI values clearly indicates that urbanization has significantly altered land cover characteristics in Varanasi over the last two decades.

G. Normalized Difference Bareness Index (NDBaI)

The Normalized Difference Bareness Index (NDBaI) was used to evaluate the distribution of barren and exposed land surfaces within the study area. Figure 9 demonstrates considerable spatial variability in barren land during the investigation period.

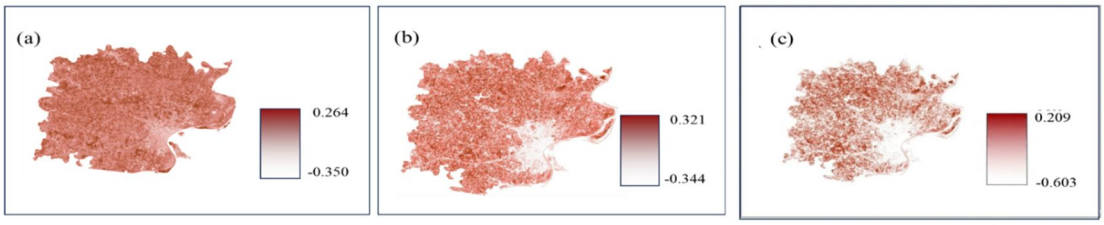


Figure 9 NDBaI of Varanasi (a) 2005 (b) 2015 (c) 2025

The areas with higher NDBaI values were mainly construction sites, exposed soil, recently deforested areas, and peri-urban areas without development. Many sites along the fringe of urban development had high NDBaI values in the early years of growth because construction was still underway and there was active land preparation for future development. As urbanisation advanced, some of the barren land parcels were increasingly being established as permanent built-up infrastructure causing small scale declines in NDBaI values. Newly emerging suburban areas, however, still showed higher bareness related to the process of urban expansion.

H. Relationship Between Land Surface Temperature and Spectral Indices

Understanding the relationship between Land Surface Temperature and environmental indicators is essential for identifying the factors controlling Urban Heat Island development. Pearson correlation analysis was therefore performed between LST and the four spectral indices (NDVI, NDWI, NDBI, and NDBaI), as given in figure 10- 13

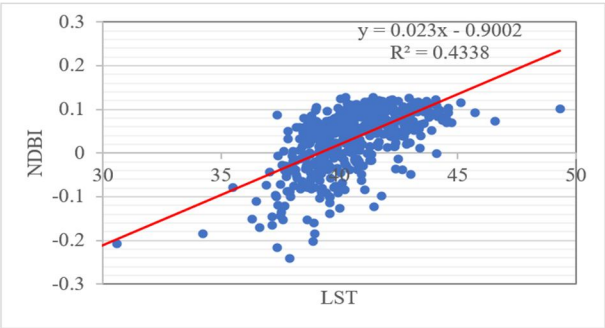


Figure 10 Correlation of LST and NDBI

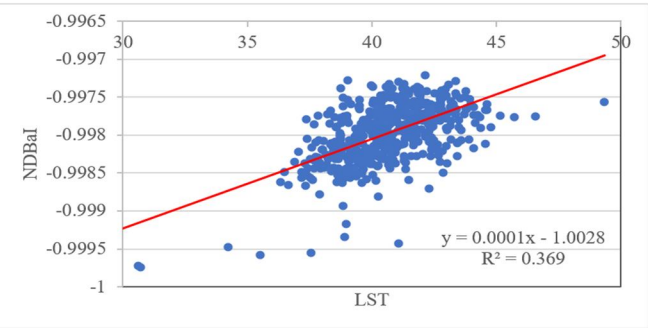


Figure 11 Correlation of LST and NDBaI

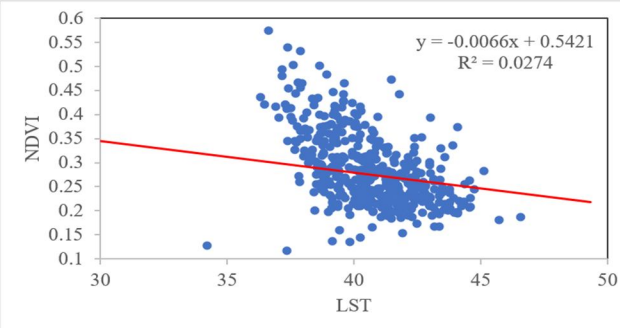


Figure 12 Correlation of LST and NDVI

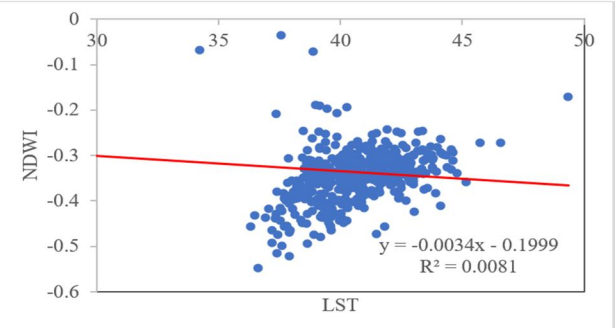


Figure 13 Correlation of LST and NDBI

The analysis showed that there was strong negative correlation between LST and NDVI, which means that higher NDVI data was associated with lesser LST data and vice versa. The urban climate moderation is achieved by the evapotranspiration, shading and surface moisture provided by the vegetation in urban areas, which decreases the thermal accumulation. This finding confirms the important role of urban green spaces in mitigating Urban Heat Island effects. Similarly, NDWI had a negative correlation with LST. The lower thermal values around the River Ganga and wetlands are due to evaporative cooling caused by moisture rich surfaces or bodies of water. On the other hand, NDBI showed a strong positive correlation with LST. The higher values of LST were obtained in the areas with high impervious surface coverage, which showed a significant improvement in heat storage and thermal radiation. This relationship is strong, indicating that built up expansion is most important in Varanasi for the intensification of temperature. Also, NDBaI had a positive correlation with LST. Soils and bare ground areas typically have lower moisture and limited vegetation, making them more prone to solar heating. The correlation between NDBaI and LST, however, was relatively low compared to that between NDBI, suggesting that the permanent built-up surfaces have more impact on the urban thermal conditions than the temporary built-up barren land. Correlation analysis shows that natural (vegetation + water bodies) have a negative correlation as natural cooling agents while built-up + barren surfaces have a positive correlation and are significant contributors to Urban Heat Island. The results are similar to those of earlier studies done in the Indian context and in other fast urbanizing areas of the world.

I. Practical Recommendations

Based on the findings of this investigation, the following recommendations are proposed to reduce Urban Heat Island intensity and promote sustainable urban development in Varanasi:

1) Urban vegetation should be expanded through large-scale plantation programmes, development of urban forests, roadside green belts, and public parks.
2) Existing water bodies, including the River Ganga, ponds, wetlands, and lakes, should be protected from encroachment to preserve their natural cooling effects.
3) Urban development policies should encourage permeable pavements, green roofs, cool roofing materials, and reflective construction materials to reduce heat absorption.
4) Future urban planning should prioritize compact and climate-resilient development while preserving ecological corridors and open spaces.
5) Routine monitoring using Remote Sensing and GIS should be incorporated into municipal planning to identify thermal hotspots and environmentally vulnerable regions.
6) Public awareness programmes should promote community participation in urban greening initiatives and sustainable environmental management.

V. CONCLUSIONS

In the present research, spatio-temporal variations in the intensity of Urban Heat Island (UHI) and Land Use Land Cover (LULC) of Varanasi city, India has been studied by employing multi-temporal Landsat satellite images as the data source and Remote Sensing and Geographic Information System (GIS) techniques. To assess the environmental changes due to high urbanization, the Land Surface Temperature (LST) and four very common spectral indices such as Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), Normalized Difference Built-up Index (NDBI), and Normalized Difference Bareness Index (NDBaI) were examined for the years of 2005, 2015, and 2025. The analysis revealed that there was significant alteration of the urban landscape in the 20 years under study. Built-up area and impervious surfaces continued to grow mostly at the cost of vegetation and open land, which shows the high rate of population growth, infrastructure development, and urbanization. The changes in land use had a marked effect on the thermal properties of the city and were also responsible for the gradual increase in the severity of the UHI phenomena. The trend of Land Surface Temperature was overall upward, with the largest values being recorded in urbanized areas that are highly developed in terms of the presence of impervious surfaces. On the other hand, comparatively low temperatures were recorded in the vegetated and water-dominated regions, such as the area along the River Ganga and urban green spaces. These findings emphasize the important role of natural ecosystems in regulating urban thermal environments. The correlation analysis also revealed a strong correlation between the environmental characteristics and the surface temperature. The relationships between NDVI, NDWI and LST were negative, supporting the fact that vegetation cover and higher moisture conditions show a strong ability to limit the thermal accumulation from evapotranspiration and evaporative cooling. NDBI and NDBaI, however, showed positive correlations with LST, suggesting that urban built-up areas and bare areas significantly add to the heat stress in urban environments.

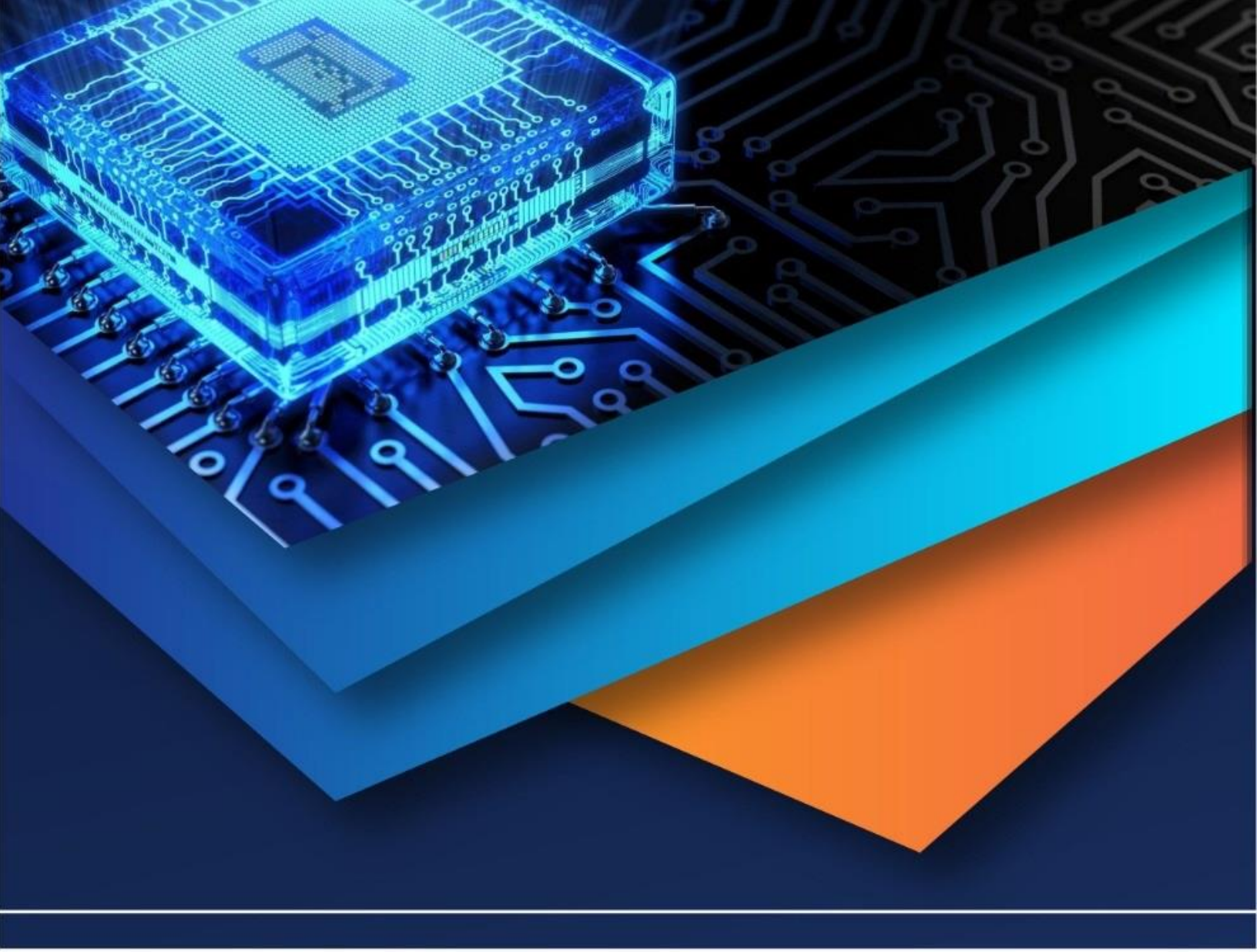
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The indices investigated had the highest influence on the intensity of Urban Heat Island in the case of built-up surfaces. Further studies could build on the current study by utilizing higher resolution satellite data (Sentinel-2, WorldView or UAV observations) to enhance the mapping accuracy. For better classification of land use and prediction of Urban Heat Island (UHI), machine learning algorithms such as Random Forest, Support Vector Machine (SVM), Gradient Boosting, XGBoost and deep learning can be applied. Cellular Automata–Markov (CA–Markov) and Artificial Neural Network (ANN) models could be used in future studies to simulate future land use scenarios and forecast the UHI expansion with various urban development pathways.

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