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A GIS-Based Weighted Overlay Approach for Mapping Urban Heat Island Intensity Zones

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Abstract: *Urban Heat Islands (UHIs) have become a significant environmental challenge in fast-growing cities, impacting local climates, public health, and energy consumption. This project focuses on identifying areas within Vijayawada that experience higher or lower heat levels by categorizing the city into different UHI intensity zones using a biophysical landscape approach. To achieve this, we used MODIS satellite data to measure Land Surface Temperature (LST) and Landsat-8 images to calculate the Normalized Difference Vegetation Index (NDVI). We also incorporated additional data layers such as built-up area density, locations of industrial zones, thermal power plants, and traffic congestion. These factors were combined through a weighted overlay analysis in GIS, with appropriate weights assigned based on their influence. The study divided Vijayawada into four distinct UHI intensity zones, reflecting the combined impact of the various factors. Findings show that densely built-up areas and industrial clusters are the main contributors to elevated surface temperatures, while vegetation plays a crucial role in cooling these areas. This information can help urban planners and local authorities design targeted strategies to mitigate the harmful effects of Urban Heat Islands in Vijayawada.*

Keywords: Urban Heat Island, LST, NDVI, Weighted Overlay Analysis, GIS

I. INTRODUCTION

Rapid urban growth has significantly altered urban landscapes by replacing natural areas with impermeable surfaces, leading to the Urban Heat Island (UHI) effect—where urban regions exhibit higher surface temperatures compared to surrounding rural areas. This phenomenon poses challenges such as adverse health effects, increased demand for cooling energy, degraded air quality, and higher rates of heat-related illnesses and deaths.

At its core, the UHI issue involves spatial analysis to determine which parts of a city serve as heat sources (hotspots) and which act as cooler zones (cold spots). While traditional methods like single-date Land Surface Temperature (LST) mapping and analyzing the correlation between LST and the Normalized Difference Vegetation Index (NDVI) have proven useful, they focus only on thermal and vegetation indicators, missing the influence of multiple contributing factors simultaneously. Biophysical landscape frameworks address this gap by integrating various land surface characteristics such as built-up density, industrial activities, and traffic congestion.

Using Weighted Overlay Analysis (WOA) within a Geographic Information System (GIS) enhances traditional approaches by combining several spatial data layers with expert-assigned weights. This method effectively captures the combined impact of all relevant factors. Such an approach is especially important for rapidly developing medium-sized cities like Vijayawada, where comprehensive UHI zoning studies are currently lacking.

This study introduces a GIS-based weighted overlay analysis framework to identify urban heat hotspots and cold spots in Vijayawada by integrating multiple biophysical factors and validating findings with ground-based meteorological observations.

Key points include:

• Combining MODIS-derived Land Surface Temperature and Landsat-8 NDVI with additional spatial layers.
• Applying weighted overlay analysis using six biophysical factors with scientifically determined weights.
• Classifying Vijayawada into four UHI intensity zones with detailed locality identification.

• Validating results using temperature data from the India Meteorological Department.

II. RELATED WORK

Gupta [1] laid the foundation for this study by identifying urban hotspots and cold spots in Delhi using a biophysical landscape framework. MODIS data derived Land Surface Temperature (LST), and Landsat-8 imagery provided the Normalized Difference Vegetation Index (NDVI). Additional layers, including built-up density, industrial areas, thermal plants, and traffic, were incorporated. A weighted overlay analysis in ArcGIS assigned weights to each factor based on its influence on UHI intensity. Delhi was classified into four UHI zones high, moderate, low, and very low with ~45% of the area, mainly central and eastern regions, as hotspots. Built-up density drove heat, while vegetation acted as a cooling factor, forming the methodological basis for this study.

In another study, Gupta [2] analyzed the spatial distribution of UHIs in Jaipur using satellite data. The city was classified into four UHI zones based on vegetation cover, built-up area, population density, industry, traffic congestion, and LST. The study highlighted built-up density and vegetation as key determinants of UHI intensity. It emphasized that rapid urban growth increases LST in heavily built-up areas, while vegetation-rich zones remain cooler. This study is relevant as it demonstrates that the relationship between built-up density and UHI intensity applies across cities of varying sizes and climatic conditions.

Pramanik and Punia [3] examined the effects of land use and land cover changes on LST and UHI distribution across districts and sub-districts in Delhi. They concluded that built-up areas act as major heat sources, while vegetation functions as the primary cooling sink. Their use of remote sensing and GIS to show the link between increasing impervious surfaces and rising temperatures directly influenced the biophysical landscape approach used in this study.

Puppala and Singh [4] investigated the UHI effect in Visakhapatnam using multi-temporal satellite imagery. They found a strong correlation between urban expansion and rising LST, and recommended mitigation strategies such as increasing green spaces and managing urban growth, particularly in coastal cities. Due to climatic and geographic similarities between Visakhapatnam and Vijayawada, this study is especially relevant.

Vani and Prasad [5] analyzed spatial and temporal land use changes and their impact on LST in Vijayawada using Landsat data. Their findings confirmed that rapid urbanization has increased surface temperatures. While the study provides useful baseline data on urban growth and LST, it is limited to these factors and does not integrate multiple biophysical variables or provide detailed UHI intensity classification.

Hang and Rahman [6] characterized the thermal environment in the National Capital Region using Landsat-8 data, illustrating how built-up density and vegetation cover influence LST. Their insights into the heterogeneous nature of thermal environments reinforce the importance of multi-factor approaches like the one applied in this study.

Mathew et al. [7] explored spatial and seasonal variations of the UHI effect in Jaipur, examining relationships with vegetation, urbanization, and elevation. Their work, which used remote sensing to map UHI intensity, reinforced the critical role of vegetation in lowering surface temperatures throughout the year. Their seasonal perspective suggests useful directions for future research building on this study.

Lastly, Sannigrahi et al. [8] analyzed how biophysical composition impacts urban surface temperatures in Greater Hyderabad. Their satellite-based study showed that areas with dense vegetation consistently had lower LST compared to densely built-up zones, supporting the sink landscape concept central to the biophysical framework used here.

III. METHODOLOGY

The Figure 1 framework for mapping urban hotspots and cold spots in Vijayawada uses a biophysical landscape approach integrating remote sensing with GIS-based weighted overlay analysis. This methodology systematically processes satellite-derived and supplementary urban data to generate a classified map of Urban Heat Island (UHI) intensity. The workflow is divided into four stages: data acquisition, preprocessing, parameter calculation, and weighted overlay classification.

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A. Data Acquisition

Three types of data were used for analysis. MODIS satellite data (MOD11A1 Version 6) from NASA's Terra and Aqua satellites provided Land Surface Temperature (LST) at 1 km resolution using thermal infrared Bands 31 and 32. Landsat-8 imagery (Level-1 Terrain Corrected) supplied red (Band 4) and near-infrared (Band 5) bands at 30 m resolution to calculate the Normalized Difference Vegetation Index (NDVI). Secondary datasets, including built-up density, industrial zones, the Vijayawada Thermal Power Station, and traffic congestion, were obtained from government agencies. Google Earth imagery supported digitization and verification. All datasets correspond to March 2020, ensuring temporal consistency.

B. Preprocessing

Before analysis, satellite data underwent preprocessing. All datasets were georeferenced to a common UTM coordinate system. Cloud masking removed cloud-covered pixels, with manual checks using true-color composites for accuracy. Radiometric calibration converted Landsat-8 digital numbers into reflectance values. All layers were resampled to 30-meter resolution for consistency. Cloud masking achieved 92% accuracy, with minor corrections for thin cirrus clouds.

C. LST and NDVI Computation

LST was derived from MODIS thermal infrared bands using a three-step radiative transfer method. Digital numbers were converted to spectral radiance, followed by brightness temperature calculation using Planck's law. This was adjusted for land surface emissivity based on NDVI to obtain accurate LST values. The temperature range for March 2020 was 27°C–35°C.

NDVI was computed from Landsat-8 red and near-infrared bands using the formula:

$$NDVI = (NIR - RED) / (NIR + RED)$$

NDVI ranges from -1 to +1, where values above 0.6 indicate dense vegetation, 0.1–0.3 represent sparse vegetation or agriculture, and near-zero or negative values indicate built-up or barren heat-generating areas.

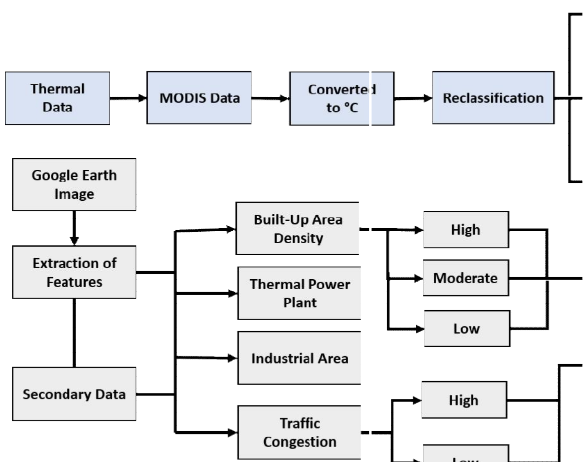

Figure 1 Proposed Methodology Flow Diagram

D. Weighted Overlay Analysis

Six spatial layers were combined using weighted overlay in GIS. Each layer was reclassified from 1 (low) to 5 (very high) based on its contribution to UHI intensity. Weights were assigned through multi-criteria analysis adapted to Vijayawada: built-up density (30%), LST (25%), industrial zones (20%), thermal plants (15%), and traffic congestion

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(10%). Composite scores were calculated as weighted sums and normalized between 1.0 and 5.0 using min-max scaling.

E. UHI Intensity Classification

Using normalized scores, Vijayawada was classified into four UHI intensity zones: High (4.0–5.0), with dense built-up areas, low vegetation, heavy traffic, and industrial influence; Moderate (3.0–3.9), with mixed land use and increasing urbanization; Low (2.0–2.9), consisting of residential areas with moderate vegetation; and Very Low (1.0–1.9), including water bodies, dense vegetation, and agricultural land. High and Moderate zones were identified as hotspots, while Low and Very Low zones were classified as cold spots.

F. Validation

Satellite-derived LST values were validated against ground temperatures from the India Meteorological Department's Vijayawada station for March 2020, using 31 daily readings. Accuracy was evaluated with RMSE and MAE, while Pearson correlation measured agreement between satellite and ground data.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The methodology was applied using MODIS and Landsat-8 data for Vijayawada for March 2020. Results include thematic maps, statistical summaries, classified UHI zones, and validation with ground temperature data, collectively identifying urban hotspots and cold spots across the city.

A. Land Surface Temperature Distribution

The LST retrieval algorithm applied to MODIS thermal infrared data for March 2020 produced a continuous temperature map of Vijayawada.

Figure 2, showing surface temperature variations in °C. Temperatures ranged from 27°C to 35°C, averaging 31.2°C with a standard deviation of ±2.1°C. The 8°C difference between warmest and coolest zones indicates a pronounced Urban Heat Island effect. Highest LST values occurred in central and eastern areas, where impervious surfaces dominate and vegetation is sparse, while lower temperatures were observed in city outskirts and along the Krishna River, where vegetation is dense and impervious surfaces minimal. This distribution confirms that urbanization and built-up density are the main drivers of elevated surface temperatures

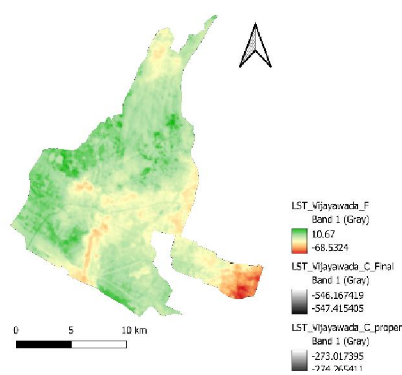

Figure 2 Land Surface Temperature of Vijayawada

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B. Vegetation Index Analysis

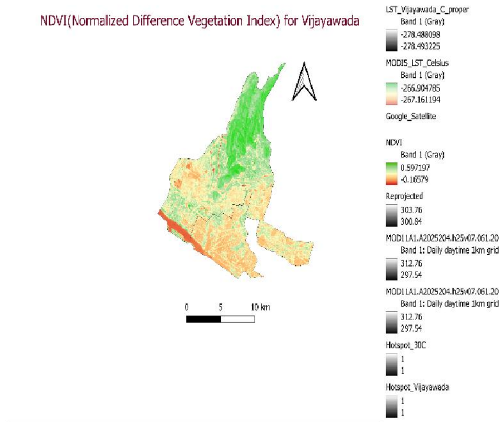

Figure 3 NDVI for Vijayawada

The NDVI algorithm applied to Landsat-8 red and near-infrared bands for March 2020 produced a map showing vegetation density across Vijayawada. NDVI values ranged from -0.092 to 0.74, with a mean of 0.28 as in Figure 3. Dense vegetation (NDVI > 0.5) was mainly along the Krishna River and western outskirts, while low NDVI (<0.1), indicating built-up or barren areas, occurred in central localities like Benz Circle, Governorpet, and One Town. About 20% of the city is vegetated, with 80% built-up, barren, or water. The mean NDVI reflects sparse to moderate vegetation, insufficient to mitigate urban heating.

The Pearson correlation between LST and NDVI was -0.72, showing a strong negative relationship. This confirms that denser vegetation reduces surface temperatures, establishing it as Vijayawada's primary cooling sink. Areas with NDVI > 0.5 had LST < 30°C, while NDVI < 0.1 corresponded to LST above 33°C.

C. Weighted Overlay Classification Results

A GIS-based weighted overlay analysis combined six spatial layers: LST, NDVI, built-up density, industrial zones, thermal power plants, and traffic congestion. Each layer was assigned weights reflecting its influence on UHI intensity, adapted from a multi-criteria analysis used in Delhi [1] and customized for Vijayawada as in Figure 4. The weights were: built-up density (30%), LST (25%), industrial zones (20%), thermal power plants (15%), and traffic congestion (10%). Each layer was reclassified on a 1–5 scale, representing its contribution to UHI intensity. The weighted sum for each pixel was calculated and normalized between 1.0 and 5.0 using min-max normalization, producing a composite UHI map showing continuous heat variations across the city.

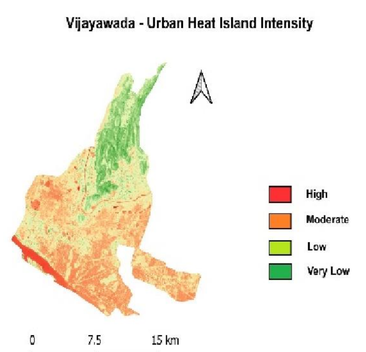

Figure 4 UHI Vijayawada

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Using the normalized scores, Vijayawada was classified into four UHI intensity zones. High UHI zones (4.0–5.0) cover 85.5 km² (15% of the city), while Moderate zones (3.0–3.9) span 171.0 km² (30%). Low UHI zones (2.0–2.9) cover 193.8 km² (34%), and Very Low zones (1.0–1.9) encompass 119.7 km² (21%). Combined, High and Moderate zones form urban hotspots (~45% of the city), whereas Low and Very Low zones constitute cold spots (~55%).

Table 1 Areas and Localities of Vijayawada under Different UHI Intensity Zones

UHI Intensity Zone	Area (sq km)	Area (%)	Names of Localities of Vijayawada
High	85.5	15.0	Benz Circle, Governorpet, One Town, Patamata, Labbipet
Moderate	171.0	30.0	Autonagar, Krishnalanka, Gunadala
Low	193.8	34.0	Mogalrajapuram, Payakapuram
Very Low	119.7	21.0	Krishna River bank, Bhavani Island, agricultural outskirts
Total	**570.0**	**100**	-

High UHI zones include Benz Circle, Governorpet, One Town, Patamata, Labbipet, and nearby industrial areas. Moderate zones cover Autonagar, Krishnalanka, and parts of Gunadala. Low zones consist mainly of residential neighborhoods with moderate vegetation, such as Mogalrajapuram and parts of Payakapuram. Very Low zones, representing naturally cool areas, include the Krishna River banks, Bhavani Island, agricultural outskirts, and peripheral forest patches. This classification provides a clear spatial understanding of heat distribution, guiding targeted UHI mitigation strategies across the city as in Table 1.

D. Validation

Satellite-derived LST values were validated against ground-based temperature data from the India Meteorological Department's Vijayawada station for March 2020. Thirty-one daily readings were compared to corresponding satellite estimates. The Mean Absolute Error (MAE) was ±1.4°C, indicating that satellite-derived LST values deviate minimally from ground measurements. The Root Mean Square Error (RMSE) was ±1.8°C, within acceptable limits for UHI studies at this resolution. The Pearson correlation coefficient of 0.85 demonstrates a strong positive relationship, confirming the reliability of the LST retrieval method and overall UHI classification.

Analysis showed that built-up area density is the most significant factor influencing UHI intensity, with densely built neighborhoods corresponding closely to High and Moderate UHI zones. Elevated surface temperatures were also observed near the Vijayawada Thermal Power Station, industrial areas in the northern and eastern sectors, and traffic hotspots at Benz Circle, M G Road, and major highway junctions. These findings reaffirm the role of built-up areas as heat sources and vegetation as cooling sinks, consistent with Gupta's Delhi study [6], which reported similar hotspot coverage (~45%) and LST ranges (27–35°C).

E. Discussion

The findings highlight the spatial distribution of Urban Heat Islands (UHIs) and the influence of biophysical landscapes on surface temperatures. Built-up density emerged as the dominant factor driving UHI intensity. Areas with more than 70% built-up cover—primarily in central, eastern, and southeastern regions—correspond to High and Moderate UHI zones. Impervious surfaces such as concrete, asphalt, and rooftops act as heat sources by absorbing and retaining solar radiation.

Industrial zones, thermal power plants, and traffic congestion further intensify UHI effects by generating heat and restricting airflow. Key industrial clusters and high-traffic corridors align with High UHI zones. Although these factors have lower weights, they amplify heat in already dense urban areas.

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The results confirm that built-up areas function as source landscapes, while vegetation acts as sink landscapes. A strong negative correlation (-0.72) between land surface temperature and vegetation index supports this relationship and validates the biophysical landscape approach.

High UHI zones consist of dense, low-vegetation areas requiring urgent mitigation. Moderate zones show mixed land use with increasing urbanization and need preventive action. Low UHI zones have moderate vegetation and stable conditions, while Very Low zones—such as water bodies and agricultural land—serve as critical cooling areas that should be preserved.

F. Other Results

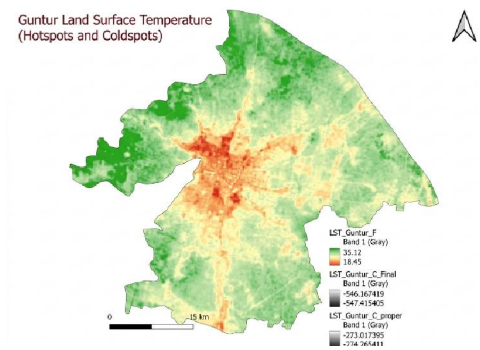

Figure 1 Land Surface Temperature of Guntur

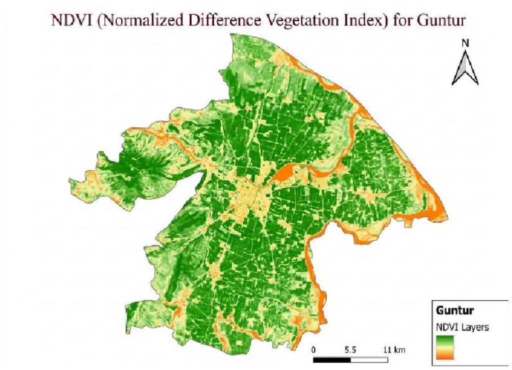

Figure 2 NDVI for Guntur

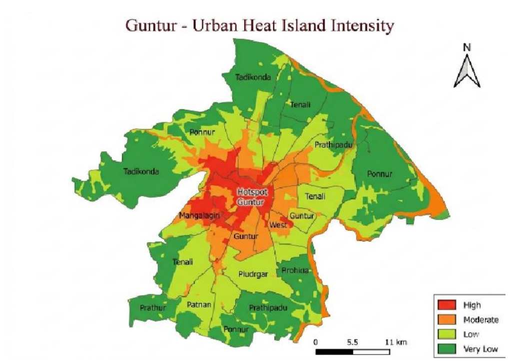

Figure 3 UHI for Guntur

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To validate the proposed methodology's regional applicability, the GIS-based weighted overlay analysis was extended to the neighboring city of Guntur. The accompanying Figure 5, Figure 6, Figure 7 and Table 2 illustrate the computed LST, NDVI, and resulting UHI intensity zones for the area. Consistent with the primary findings, densely built-up sectors emerged as high-intensity urban hotspots, while vegetation acted as an effective cooling sink.

Table 2 Areas and Localities of Guntur under Different UHI Intensity Zones

UHI Intensity Zone	Area (sq km)	Area (%)	Names of Localities
High	16.8	12.0	Brodipet, Arundelpet, Lakshmipuram, Guntur Railway Station area, Nallapadu Road
Moderate	49.0	35.0	Pattabhipuram, Vidyanagar, Chowdavaram, Pedapalakaluru, Gorantla
Low	49.0	35.0	Brindavan Gardens, Etukuru, Nallapadu (outskirts), Reddypalem (periphery)
Very Low	25.2	18.0	Agricultural fields along NH-16 bypass, rural pockets near the Guntur-Krishna canal
Total	**140.0**	**100**	-

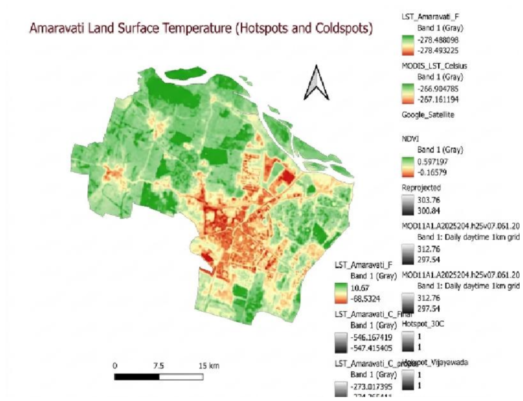

Figure 8 Land Surface Temperature of Amaravathi

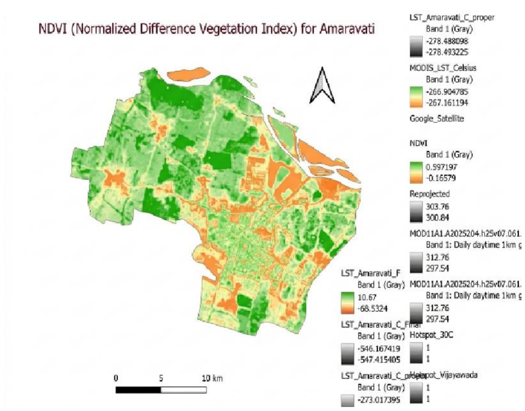

Figure 9 NDVI for Amaravathi

Similarly, a UHI intensity classification was conducted for the Amaravati region. The Figure 8,Figure 9,Figure 10 and Table 3 present the LST variations, NDVI distribution, and the final composite heat map for the area. Visual analysis of these results reaffirms the strong inverse relationship between surface temperature and vegetation density across Amaravati's distinct urban landscape.

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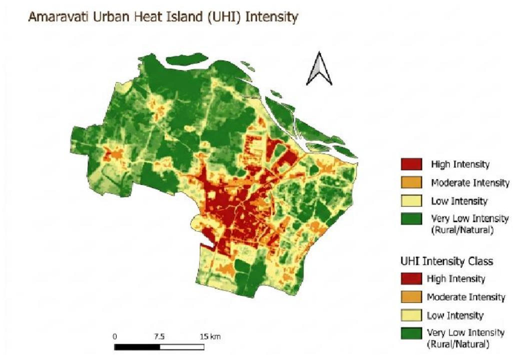

Figure 10 UHI for Amaravathi

Table 3 Areas and Localities of Amaravathi under Different UHI Intensity Zones

V. CONCLUSION

This study mapped urban hotspots and cold spots in Vijayawada using a biophysical landscape framework integrating remote sensing and GIS-based weighted overlay analysis. It addresses the limited spatial understanding of Urban Heat Island (UHI) intensity in this rapidly expanding city, which has received less attention than major metros like Delhi.

Land Surface Temperature (LST) analysis for March 2020 showed values ranging from 27°C to 35°C, with an average of 31.2°C. The 8°C variation indicates a strong UHI effect, with the highest temperatures in central and eastern areas dominated by impervious surfaces and low vegetation. Cooler zones were mainly observed along the Krishna River and city outskirts.

NDVI values (-0.092 to 0.74, mean 0.28) identified vegetation as a key cooling factor. A strong negative correlation (-0.72) between LST and NDVI confirms that areas with denser vegetation experience lower temperatures. Built-up density emerged as the primary driver of UHI, especially in central and southeastern zones, while industries, thermal plants, and traffic further intensified heat.

The city was classified into four UHI zones: High (15%), Moderate (30%), Low (34%), and Very Low (21%). Hotspots cover about 45% of the area, mainly in central regions, while cold spots (55%) are concentrated in peripheral and river-adjacent areas.

Validation with India Meteorological Department data showed high accuracy ($R^2 = 0.85$). The findings highlight targeted strategies such as increasing green cover, adopting cool materials, and preserving low-UHI zones for sustainable urban development.

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