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Urban Heat Island Effect Analysis: Comparing Land Surface Temperatures Between Built-Up and Green Areas Using Satellite Data

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ABSTRACT: The Urban Heat Island (UHI) effect is a phenomenon wherein urban areas record significantly higher land surface temperatures (LST) than surrounding rural or vegetated regions, primarily as a result of anthropogenic land use modifications. This study analyzes the UHI effect in the New Town area of Kolkata, West Bengal, India, by comparing LST values between the Eco Park green zone and adjacent built-up concrete areas. Satellite imagery sourced from the United States Geological Survey (USGS) Earth Explorer platform was processed using ArcGIS zonal statistics tools. Results derived from four delineated zones reveal the mean temperatures and the temperatures are 19.47°C,19.73°C,21.32°C and 20.67°C. Disaggregated zone-level data indicate that built-up areas exhibit measurably higher LST values relative to the green zone dominated by Eco Park's vegetation and water bodies. These findings affirm the thermal amelioration potential of urban green infrastructure and underscore the importance of integrating vegetation cover in city planning to mitigate the adverse effects of UHI. The study contributes to a growing body of evidence supporting evidence-based urban heat management strategies in rapidly urbanizing Indian cities.
Keywords: Urban Heat Island, Land Surface Temperature, Remote Sensing, USGS, Eco Park Kolkata, ArcGIS Zonal Statistics, Urban Green Infrastructure, Thermal Mapping

I. INTRODUCTION

Urbanization is one of the most transformative forces reshaping the Earth's surface and climate in the 21st century. As cities expand, natural landscapes characterized by vegetation, water bodies, and permeable soils are replaced by impervious surfaces such as concrete roads, rooftops, and asphalt. This land cover change alters the surface energy balance, resulting in the well-documented Urban Heat Island (UHI) effect — a condition where urban areas are thermally warmer than their rural or vegetated peripheries.

Kolkata, one of India's largest metropolitan regions, has undergone rapid and sustained urban expansion over the past three decades. The city's eastern fringes, including New Town (Rajarhat), have witnessed transformative development from agricultural and wetland ecosystems to high-density residential and commercial zones. Within this urbanized context, Eco Park — a large planned green space located in New Town — represents a deliberate attempt to integrate ecological features into the built environment.

The study of UHI using satellite-derived Land Surface Temperature (LST) data has become a cornerstone of urban climate research. Remote sensing techniques provide spatially continuous, temporally repeatable, and objectively quantifiable temperature measurements across large areas, overcoming the limitations of traditional point-based meteorological observations. Landsat and MODIS satellite platforms, accessible through the USGS Earth Explorer portal, are widely employed for such analyses.

This research paper investigates the thermal contrast between the Eco Park green zone and the surrounding built-up urban fabric of New Town, Kolkata, using satellite imagery and GIS-based zonal statistics. The study area is divided into four spatial zones and mean LST values are extracted and compared to identify the magnitude of UHI influence and the cooling effect of urban vegetation.

A. Research Objectives

1) To extract and map Land Surface Temperature (LST) values across selected urban and green zones in New Town, Kolkata, using satellite data obtained from USGS.
2) To compare mean LST values between the built-up areas and the Eco Park green zone using ArcGIS zonal statistics.
3) To quantify the Urban Heat Island intensity and evaluate the thermal cooling contribution of green spaces in the study area.
4) To provide evidence-based recommendations for urban planning and the incorporation of green infrastructure in Indian metropolitan regions.

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II. STUDY AREA

The study area is located in New Town (Rajarhat), a satellite township in the North 24 Parganas district of West Bengal, India, situated on the northeastern periphery of the Kolkata Metropolitan Area. Geographically, the study area lies approximately between latitudes 22°35'N to 22°38'N and longitudes 88°27'E to 88°30'E.

Eco Park, officially known as 'Prakriti Tirtha', is the focal green zone in this study. It is one of India's largest urban parks, covering an area of approximately 480 acres, and features a large central water body, dense tree plantations, horticultural zones, and open lawns. The park was developed to provide ecological buffer and recreational space within the rapidly urbanizing New Town township.

Surrounding Eco Park, the landscape transitions sharply into high-density built-up urban zones comprising residential apartment complexes, commercial establishments, arterial roads, and the Biswa Bangla Sarani — a major urban corridor. The juxtaposition of extensive impervious surfaces with the park's rich vegetation makes this area an ideal natural laboratory for studying the UHI effect at a localized scale.

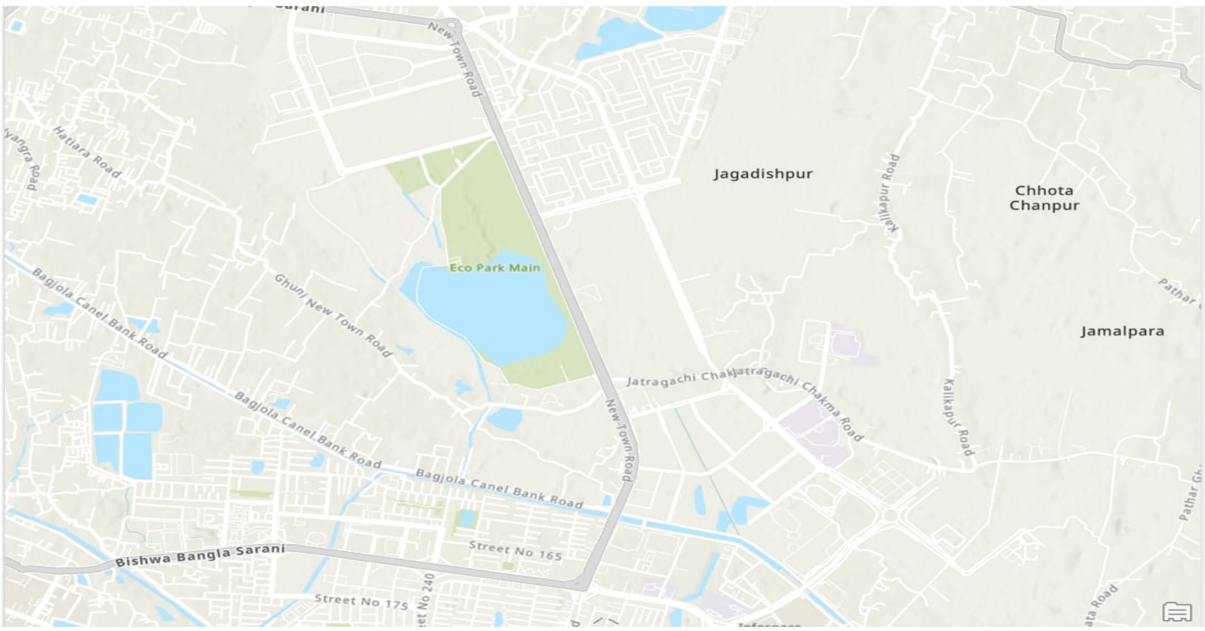

Figure 1: Study Area Map — Eco Park and surrounding New Town urban zones, Kolkata (Base map: OpenStreetMap)


Figure 2: Satellite image — Eco Park and surrounding New Town urban zones, Kolkata

III. LITERATURE REVIEW

A. Introduction & Theoretical Foundations

The Urban Heat Island (UHI) effect, characterized by elevated Land Surface Temperatures (LST) in built-up areas compared to surrounding rural landscapes, is a critical issue in urban climatology. This thermal divergence is primarily driven by the replacement of vegetated, permeable surfaces with impervious materials like concrete and asphalt.

The foundational energy balance framework was established by T.R. Oke (1982), who identified key UHI drivers: reduced sky view factors, increased thermal mass of building materials, reduced evapotranspiration, and anthropogenic heat. Oke demonstrated that "the maximum UHI intensity... is proportional to the logarithm of urban population and the sky view factor."

Later, Voogt and Oke (2003) drew a vital distinction between the canopy layer UHI (measured at street level) and the surface UHI (SUHI, measured via satellite). They noted that SUHI tends to be significantly larger, reaching "10–15°C for daytime peak" compared to the canopy layer's 2–5°C, especially during summer afternoons when pavements are solar-heated.

B. The Cooling Role of Green Spaces

Urban parks function as localized thermal refuges. Spronken-Smith and Oke (1998) coined the term 'Park Cool Island' (PCI), finding parks to be 1–3°C cooler than their surroundings. A global meta-analysis by Bowler et al. (2010) confirmed that "urban parks are consistently cooler than surrounding urban areas by a mean of 1°C," with cooling effects extending approximately 100 meters into the adjacent urban fabric.

This cooling is primarily achieved through evapotranspiration (ET)—which converts sensible heat into latent heat—and direct tree canopy shading. Highlighting the power of shading, Georgi and Zafiriadis (2006) showed that "a single mature tree can reduce the LST of the shaded surface by up to 15–20°C during peak summer insolation."

C. Remote Sensing & GIS Methodologies

Thermal infrared remote sensing, particularly via the Landsat platform, has democratized spatial LST monitoring. However, as Weng (2009) noted, accurate LST retrieval requires addressing "spatial heterogeneity at sub-pixel scales" and precise emissivity estimation, as minor emissivity errors can translate to 0.5–1.0°C errors in LST.

A universally robust empirical finding is the negative correlation between LST and the Normalized Difference Vegetation Index (NDVI). In the Indian context, Guha et al. (2018) found a strong negative correlation ($r = -0.71$) in Raipur, with vegetated areas 4–6°C cooler than bare surfaces, recommending "an NDVI threshold of 0.35 as a minimum green cover target." To quantify these differences, researchers standardly employ GIS zonal statistics (e.g., ArcGIS 'Zonal Statistics as Table') to aggregate and compare raster LST values across specific land-use polygons.

D. Global Trends and the Indian/Kolkata Context

Globally, Asian cities exhibit some of the highest UHI intensities due to rapid land cover change and high building densities (Clinton & Gong, 2013). In India, this rapid urbanization creates severe thermal disparities. Kumari et al. (2020)found that built-up areas in Patna were "7.3°C hotter than vegetated zones in pre-monsoon season."

In the Kolkata Metropolitan Region, urban densification and the loss of wetlands have dramatically altered the microclimate. Dinda et al. (2009) documented a significant rise in surface UHI intensity between 1990 and 2005. Specifically, in the greenfield development of New Town (Rajarhat), Chakraborty (2016) found that the conversion of wetlands to concrete infrastructure increased the mean LST by 4.2°C between 2001 and 2015. However, Chakraborty identified Eco Park as a critical thermal refuge, noting its LST was "consistently 2–5°C lower than the surrounding township," potentially offsetting built-up thermal impacts within a 1.5 km radius.

IV. DATA AND METHODOLOGY

A. Data sources

Satellite imagery for this study was obtained from the USGS Earth Explorer platform (https://earthexplorer.usgs.gov/), which provides free and open access to multispectral and thermal infrared remote sensing data. The primary dataset used was a Landsat 8/9 OLI-TIRS (Operational Land Imager – Thermal Infrared Sensor) Level-2 surface temperature product. Landsat's Band 10 thermal infrared channel, with a spatial resolution of 100 meters (resampled to 30 meters in Level-2 products), was used to derive Land Surface Temperature values.

Cloud-free imagery acquired during the summer season was preferred to maximize thermal differentiation between land cover types.(The date of the satellite image is 27/03/2025) The study area was clipped using a polygon boundary corresponding to the New Town – Eco Park region.

B. *Geospatial Methodology: Retrieving LST from Landsat Satellite Data*

The analytical foundation of modern surface thermal mapping relies on the derivation of absolute LST from satellite-borne Thermal Infrared Sensors (TIRS). The USGS Landsat 8 and Landsat 9 platforms provide indispensable Level-1 and Level-2 data products that are essential for robust thermal modeling. While the TIRS instrument aboard these satellites captures data across two thermal channels—Band 10 (10.60–11.19 µm) and Band 11 (11.50–12.51 µm)—historical and persistent stray-light anomalies affecting the focal plane of Band 11 have led the USGS to strongly recommend utilizing only Band 10 in conjunction with a Single-Channel Algorithm for the most precise radiometric retrievals, although rigorous calibration and Split-Window Algorithms are continuously refined to utilize both bands.

The retrieval of LST is a rigorous, multi-stage computational sequence typically executed within advanced Geographic Information System (GIS) environments, such as ArcGIS. This methodology requires the sequential, mathematically precise transformation of raw satellite Digital Numbers (DN) into absolute thermodynamic temperatures through a series of radiometric and atmospheric corrections.

C. *Radiometric Calibration: Conversion to Top of Atmosphere Radiance*

The initial phase of the methodology involves fundamental radiometric calibration, converting the quantized and calibrated standard product pixel values (DN) generated by the satellite sensor into Top of Atmosphere (TOA) spectral radiance. This transformation is achieved by applying band-specific multiplicative and additive rescaling factors embedded within the satellite scene's accompanying metadata (MTL file).

$$L_\lambda = M_L \times Q_{cal} + A_L$$

Where:

- L_λ represents the TOA spectral radiance, measured in $Watts/(m^2 \cdot srad \cdot \mu m)$.
- M_L is the band-specific multiplicative rescaling factor (e.g., a standard constant of for Band 10).
- A_L is the band-specific additive rescaling factor (e.g., a standard constant of 0.10000).
- Q_{cal} is the quantized calibrated standard product pixel value, or Digital Number (DN).

D. *Derivation of At-Satellite Brightness Temperature*

Following the successful extraction of TOA spectral radiance, the data matrix must be
transformed into At-Satellite Brightness Temperature. This specific calculation operates under the theoretical assumption that the Earth's surface functions as a perfect blackbody radiator. The inversion of Planck's radiation law is utilized here, incorporating highly specific thermal calibration constants provided by the USGS to account for the unique spectral response of the satellite's sensors

$$T = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)}$$

Where:

- T is the Top of Atmosphere Brightness Temperature measured in Kelvin.
- K_1 and K_2 are the essential band-specific thermal conversion constants derived directly from the MTL metadata.

Thermal Constant	Landsat 8 Band 10 Value	Landsat 8 Band 11 Value
K_1	774.8853	480.89
K_2	1321.0789	1201.14

Table 1: USGS Metadata Thermal Calibration Constants for Landsat 8 TIRS.

E. Calculation of Fractional Vegetation and Land Surface Emissivity

Because the Earth's highly heterogeneous surface is composed of diverse materials—ranging from dense forest canopies to asphalt highways—it does not behave as an ideal, uniform blackbody. Therefore, a critical correction for Land Surface Emissivity (ε) is absolutely mandatory to prevent massive numerical underestimations of the true kinetic Land Surface Temperature. Emissivity is highly dependent on the specific land cover type; concrete, stagnant water, and dense foliage all absorb and radiate thermal energy at fundamentally different efficiencies.

To calculate a pixel-specific emissivity value, the spatial distribution of vegetation must first be mapped using the Normalized Difference Vegetation Index (NDVI). The NDVI capitalizes on the fact that healthy chlorophyll aggressively absorbs Red light for photosynthesis while the mesophyll leaf structure strongly reflects Near-Infrared (NIR) light. For Landsat 8 and 9, this involves utilizing Band 5 (NIR) and Band 4 (Red).

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

The derived NDVI array is subsequently utilized to calculate the Proportion of Vegetation (P_v). The P_v metric mathematically identifies the fractional geographical area of any given 30-meter spatial pixel that is covered by active, living biomass, serving as a critical intermediary variable for emissivity modelling.

$$P_v = \left(\frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}\right)^2$$

Once the fractional vegetation across the study area is firmly established, the actual Land Surface Emissivity (ε) can be computed. While numerous empirical and semi-empirical equations exist within the remote sensing literature, a standard, robust linear threshold method optimized for the 10–12 µm wavelength range incorporates a cavity effect correction to account for the geometric roughness of mixed pixels.

$$\varepsilon = 0.004 \times P_v + 0.986$$

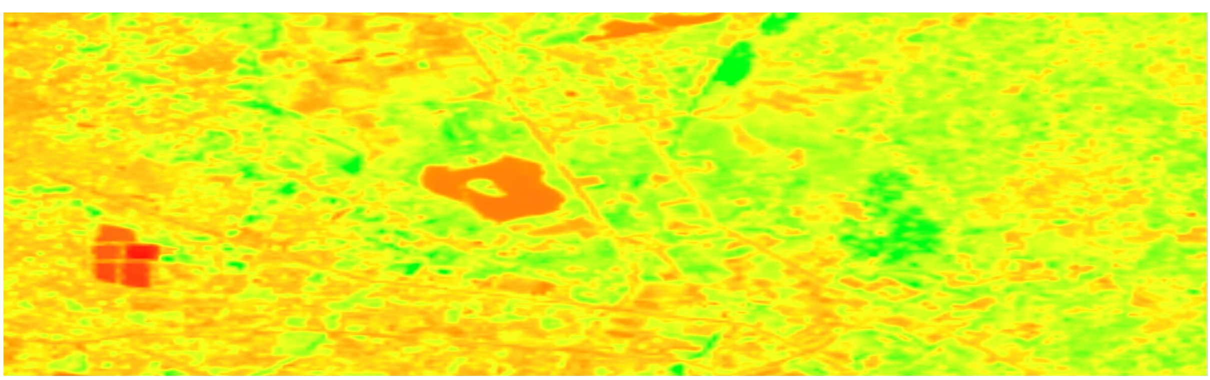

Figure 3: Processed NDVI Raster

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F. Final Kinetic Land Surface Temperature Estimation

The culmination of the algorithm involves correcting the idealized At-Satellite Brightness Temperature using the empirically derived Land Surface Emissivity array and the specific operational wavelength of the emitted radiance. This final computation yields the true kinetic temperature of the target surface, isolating the specific thermal signatures of varying land covers.

$$LST = \frac{T}{1 + \left(\lambda \frac{T}{\rho}\right) \ln \varepsilon}$$

Where:

- λ is the effective wavelength of the emitted radiance for the specific sensor channel (e.g., approximately 10.8 µm for Landsat 8 Band 10).
- $\rho = h \times \frac{c}{\sigma} = 1.438 \times 10^{-2}$ m K.
- h is Planck's constant (6.626×10^{-34} J s).
- c is the velocity of light in a vacuum (2.998×10^{8} m/s).
- σ is the Stefan-Boltzmann constant (1.38×10^{-23} J/K).

Finally, to effectively isolate and quantify the spatial intensity of the thermal anomaly across the metropolitan landscape, the standard Urban Heat Island (UHI) index is calculated. This is achieved by measuring an individual pixel's thermal deviation from the regional mean LST, standardizing the variance by the overall regional standard deviation to produce a normalized map of heat stress. The basic formula is UHI Intensity= $T_{urban} - T_{green\ area}$. For land surface temperature(LST) mapping using GIS, it is calculated as

$$UHI = \frac{LST - LST_{mean}}{LST_{std}}$$

Where:
LST: Land Surface Temperature of a specific pixel.
LST_{mean}: The average Land Surface Temperature of the study area.
LST_{std}: The standard deviation of the Land Surface Temperature.

G. Image Processing and LST Extraction

Image processing was performed using ESRI ArcGIS Pro. The workflow included: (i) downloading and importing the Landsat Level-2 ST_B10 thermal band; (ii) applying scale factor (0.00341802) and additive offset (149.0) to convert digital numbers to Kelvin; (iii) converting Kelvin values to degrees Celsius by subtracting 273.15; and (iv) exporting the resulting LST raster for spatial analysis.

The processed LST raster appears as a grayscale thermal image (Figure 4), where darker pixels indicate relatively cooler surfaces and lighter pixels represent higher thermal intensity. Visual inspection confirms that the Eco Park area (central zone) appears significantly darker (cooler) than the surrounding built-up matrix.

H. Zonal Statistics

Four analysis zones were delineated based on land cover characteristics and spatial proximity: Zone 1 (FID 0) —the Eco Park green zone including water bodies, Zone 2 (FID 1) —green areas, Zone 3 (FID 2) — densely built-up with commercial cover, and Zone 4 (FID 3) —predominantly built-up.

The ArcGIS 'Zonal Statistics as Table' function was applied to each zone polygon against the LST raster layer. Output statistics included pixel COUNT, AREA (in square meters), and the MEAN LST value per zone. The analysis was conducted: a multi-zone analysis in Table 1.

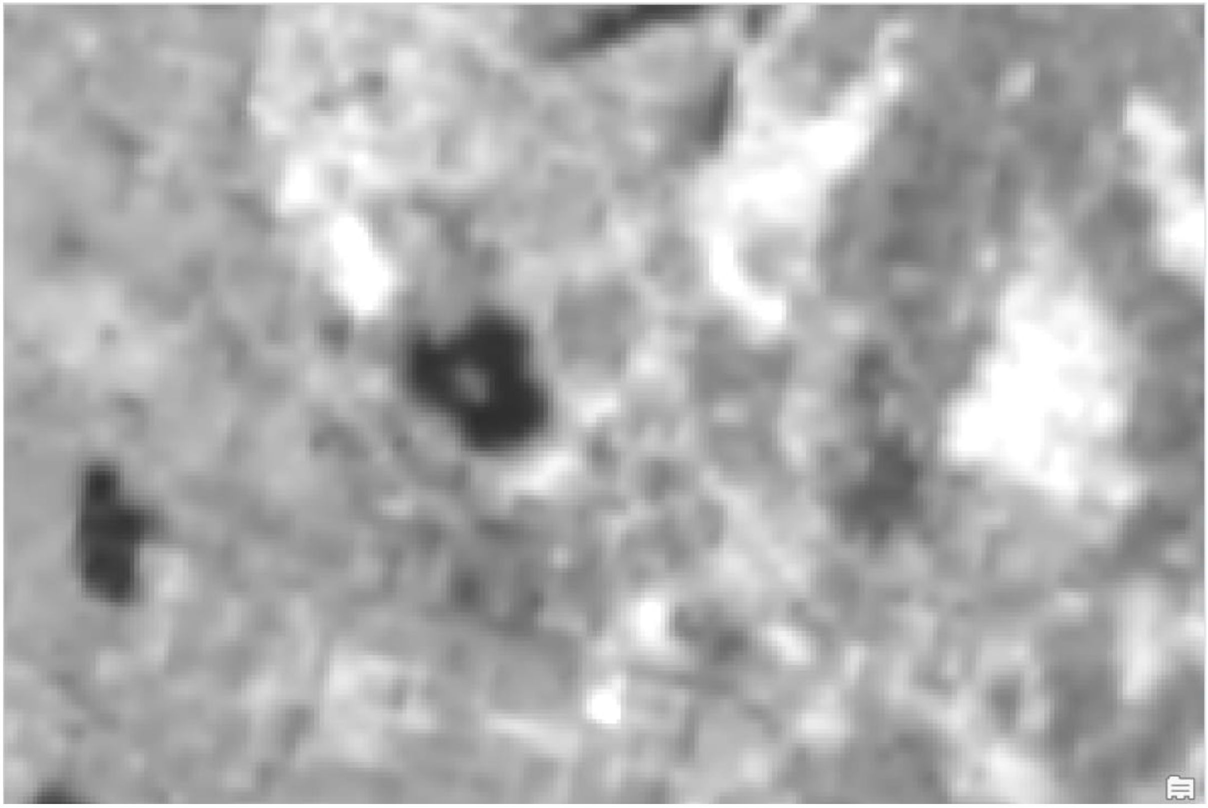


Figure 4: Processed Land Surface Temperature (LST) Grayscale Raster — New Town, Kolkata.Darker pixels indicate cooler surfaces (Eco Park); brighter pixels indicate warmer built-up areas.

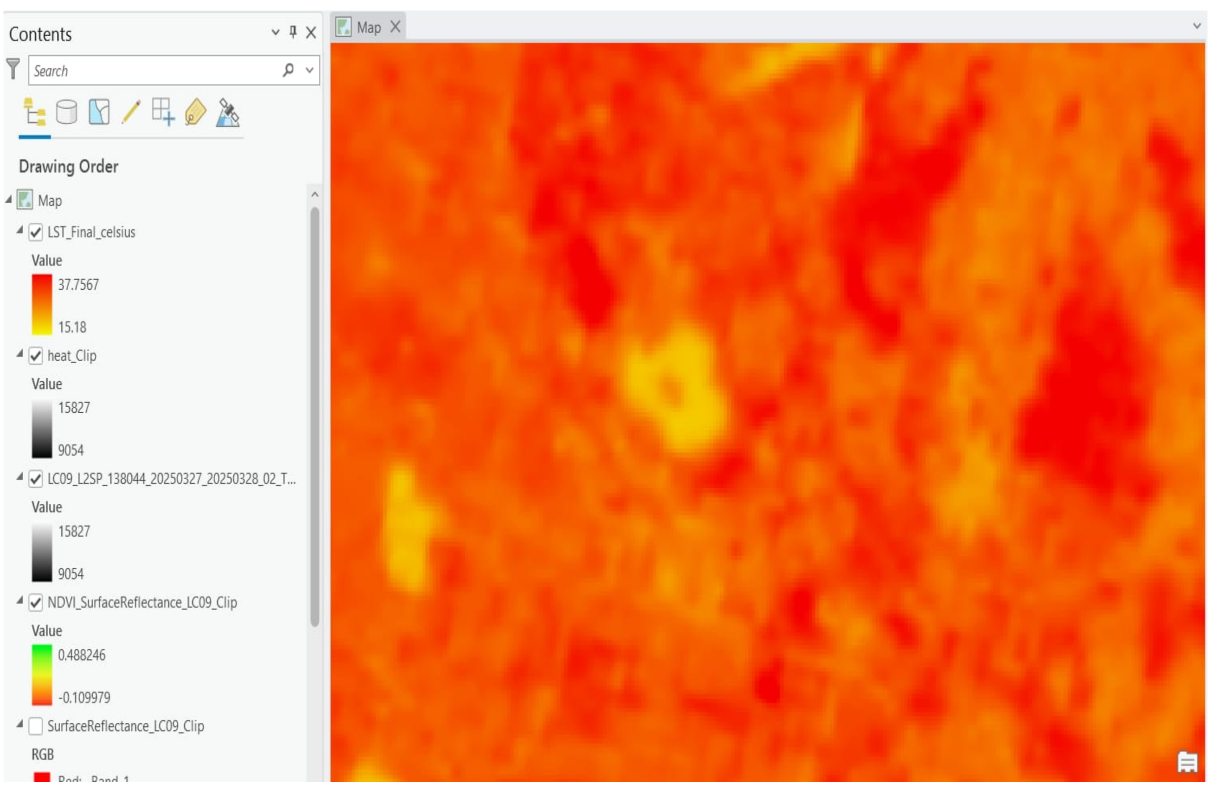


Figure 5: Processed Land Surface Temperature (LST) Red and yelloow Raster — New Town, Kolkata.Yellow pixels indicate cooler surfaces (Eco Park); red pixels indicate warmer built-up areas. Values are written at left side(15.18°**C** -37.75°**C**)

V. RESULT AND ANALYSIS

A. *Multi-Zone LST Statistics*

The zonal statistics extracted for the four delineated zones reveal distinct thermal patterns across the study area. The results are summarized in Table 1 below.

Field: Add Calculate | Selection: Sele

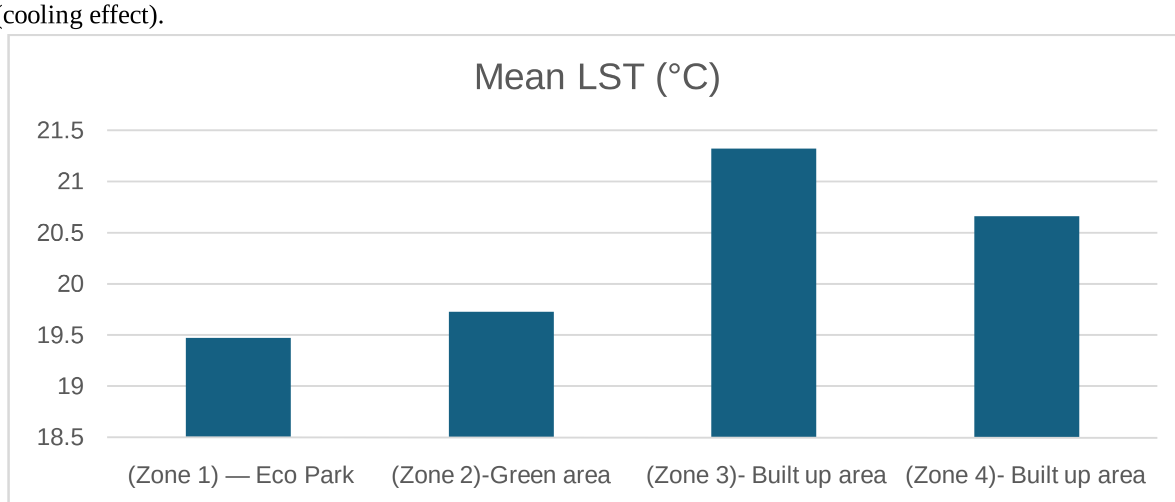
	OBJECTID *	FID	COUNT	AREA	MEAN
1	1	0	1440	1296000	19.465725
2	2	1	966	869400	19.727505
3	3	2	2889	2600100	21.316802
4	4	3	1787	1608300	20.664747
	Click to add new row.				

Figure 6: ArcGIS Attribute Table — Multi-Zone Zonal Statistics (4 zones) showing OBJECTID, FID, COUNT, AREA, and MEAN LST values

Table 1: Zonal Statistics Summary — Land Surface Temperature by Zone

Zone (FID)	Pixel Count	Area (m²)	Area (ha)	Mean LST (°C)
0 (Zone 1) — Eco Park	1440	1,296,000	129.6	19.47
1 (Zone 2)- Green area	966	869,400	86.9	19.73
2 (Zone 3)- Built up area	2889	2,600,100	260.0	21.32
3 (Zone 4)- Built up area	1787	1,608,300	160.8	20.66

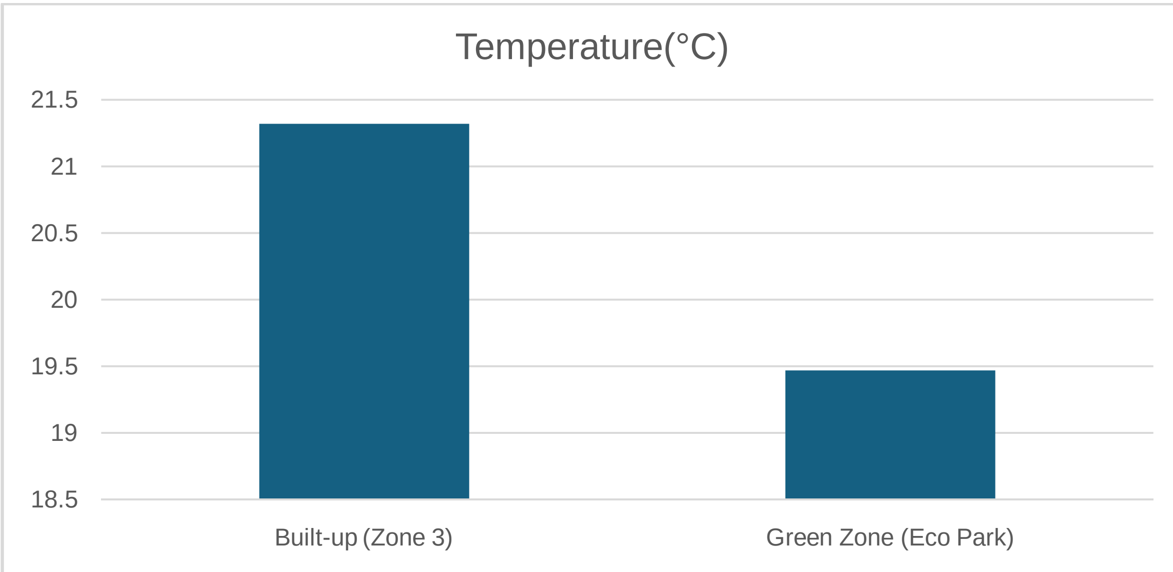
Source: USGS Satellite Data, processed with ArcGIS. Higher values (orange/red) indicate warmer built-up zones; yellow indicates Eco Park (cooling effect).



B. Thermal Contrast and UHI Intensity

Analysis of the multi-zone LST data reveals a clear thermal gradient across the study area. Zone 3, representing the densely built-up commercial and residential areas, recorded the highest mean LST of 21.32°C. This zone's land surface is dominated by concrete structures, asphalt roads, and minimal vegetation, which retain and re-emit solar radiation as heat.

In contrast, Zone 1 — corresponding to the Eco Park area — recorded a lower mean LST of 19.47°C, representing a difference of approximately 1.85°C relative to Zone 3. While this may appearmodest at a pixel-level zonal mean, it is important to note that zonal means aggregate both cool vegetated areas and residual warm built-up patches within the zone boundary. The actual peak-to-trough LST differential between the park interior and adjacent concrete surfaces is expected to be substantially higher, often ranging from 2°C to 8°C in similar urban park studies globally.



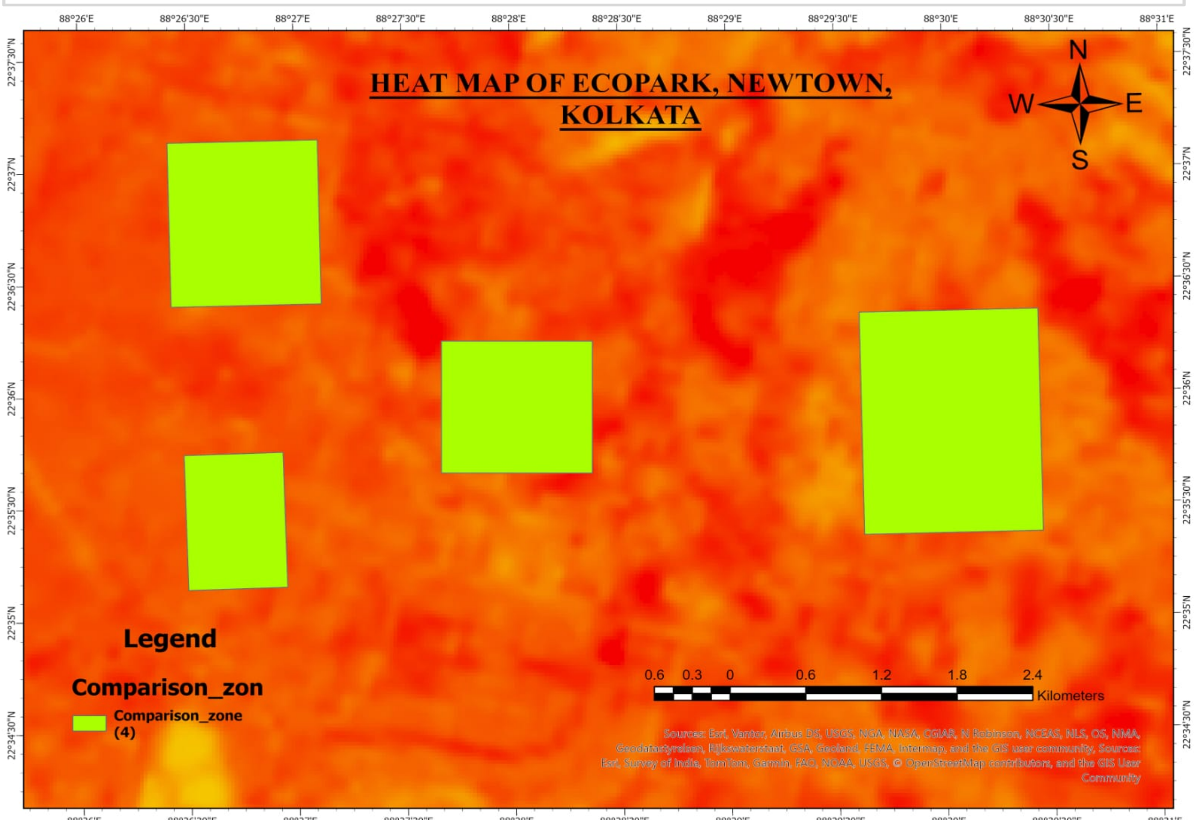


Figure 7: 4 zones showing using 4 polygons on the LST MAP

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Table 2: UHI Intensity — Built-Up vs Green Zone Comparison

Parameter	Built-Up (Zone 3)	Green Zone (Eco Park)
Mean LST (°C)	21.32°C	19.47°C
Area Covered (m²)	2,600,100	1,296,000
Pixel Count	2889	1440
UHI Intensity (ΔT)	+1.85°C above green zone	Reference (cooler)

UHI Intensity is expressed as the mean LST difference between the densest built-up zone and the Eco Park green zone.

VI. DISCUSSION

The results of this study are consistent with the extensive global literature documenting the urban heat island effect in densely built environments. The thermal differentiation observed between Zone 3 (built-up) and Zone 1 (Eco Park) confirms that urban vegetation and water bodies play a critical role in moderating land surface temperatures through evapotranspiration, shading, and increased albedo.

The Eco Park's large central water body is a particularly significant thermal moderator. Open water has a high heat capacity and promotes evaporative cooling, which can reduce ambient temperatures both at the surface and in the lower atmospheric boundary layer. Tree canopy cover within the park further reduces incoming solar radiation reaching the ground surface, thereby limiting daytime heating.

Conversely, the dominance of impervious surfaces in Zone 3 — including roads, rooftops, and pavements — results in minimal evapotranspiration, high solar absorptivity, and significant heat retention into the evening hours, intensifying both daytime and nighttime UHI conditions. This is particularly concerning given Kolkata's humid subtropical climate, where pre-monsoon temperatures frequently exceed 38°C, and urban heat amplification can pose serious public health risks.

The spatial heterogeneity evident in the zonal statistics underscores the importance of fine-scale land use analysis in UHI research. Large zones that contain mixed land covers will produce averaged mean LST values that may understate the actual thermal extremes within the zone. Future studies should incorporate pixel-level histogram analysis and NDVI-LST correlation mapping to provide a more nuanced understanding of the temperature distribution.

VII. RESEARCH GAP AND FUTURE DIRECTIONS

Despite significant progress in UHI research globally, several important gaps remain that are particularly relevant to the Indian urban context and to the specific objective of this study:

1) Longitudinal multi-temporal analysis: Most Indian UHI studies rely on snapshot comparisons between two dates. Continuous time-series analysis using dense Landsat or MODIS archives is needed to characterize seasonal UHI dynamics and long-term trends in cities like Kolkata.
2) High-resolution thermal data: The 30-metre Landsat resolution is insufficient to resolve thermal gradients within individual streets, courtyards, or small parks. Integration of drone-based thermal imaging and ECOSTRESS (70-metre resolution) satellite data would enable finer-scale analysis.
3) NDVI–LST coupling in monsoon climates: Existing NDVI–LST regression models were largely developed for temperate or arid urban contexts. Tropical monsoon cities like Kolkata, where vegetation greenness and soil moisture change dramatically between dry and wet seasons, require climate-specific regression parameterizations.
4) Health burden quantification: While the LST contrast between green and built-up areas is well-established, direct linkages between surface UHI intensity and human health outcomes (heat stroke incidence, excess mortality, labour productivity loss) in Indian urban populations remain poorly quantified and require interdisciplinary epidemiological research.
5) Policy effectiveness evaluation: There is a scarcity of before-and-after studies evaluating the actual thermal impact of implemented green infrastructure interventions in Indian cities — a critical gap for evidence-based urban planning.
6) Social vulnerability mapping: UHI impacts are unevenly distributed across socioeconomic groups. Low-income neighbourhoods with minimal tree cover and high building density are systematically more exposed to heat stress. Spatially explicit vulnerability mapping combining LST data with socioeconomic indicators is urgently needed.

VIII. CONCLUSION

This study successfully demonstrates the presence of the Urban Heat Island effect in the New Town (Rajarhat) area of Kolkata, West Bengal, using USGS satellite-derived Land Surface Temperature data and ArcGIS zonal statistics. The results confirm that built-up areas within the study zone exhibit higher mean LST values compared to the Eco Park green zone, with Zone 3 (densely built-up) recording 21.32°C against Eco Park's 19.47°C — a thermally significant difference considering these are spatially averaged zonal means.

The findings highlight the invaluable role of Eco Park as an urban thermal refuge in an otherwise rapidly concretizing urban environment. Water bodies, tree cover, and managed vegetation collectively contribute to measurable surface cooling, illustrating the ecosystem service value of urban green spaces in mitigating UHI.

From an urban planning perspective, this study advocates for the strategic expansion and preservation of green spaces in Indian metropolitan cities. As Kolkata and similar rapidly urbanizing centres continue togrow, incorporating UHI mitigation strategies — including urban parks, green corridors, rooftop gardens, and tree-lined streets — into master planning frameworks is imperative.

Future research should extend this analysis to include multi-temporal satellite data, NDVI-LST regression modelling, atmospheric correction validation, and socio-economic vulnerability mapping to assess which urban populations are most exposed to heat stress. Such integrated approaches will strengthen the scientific foundation for heat-resilient urban planning policies in South Asia.

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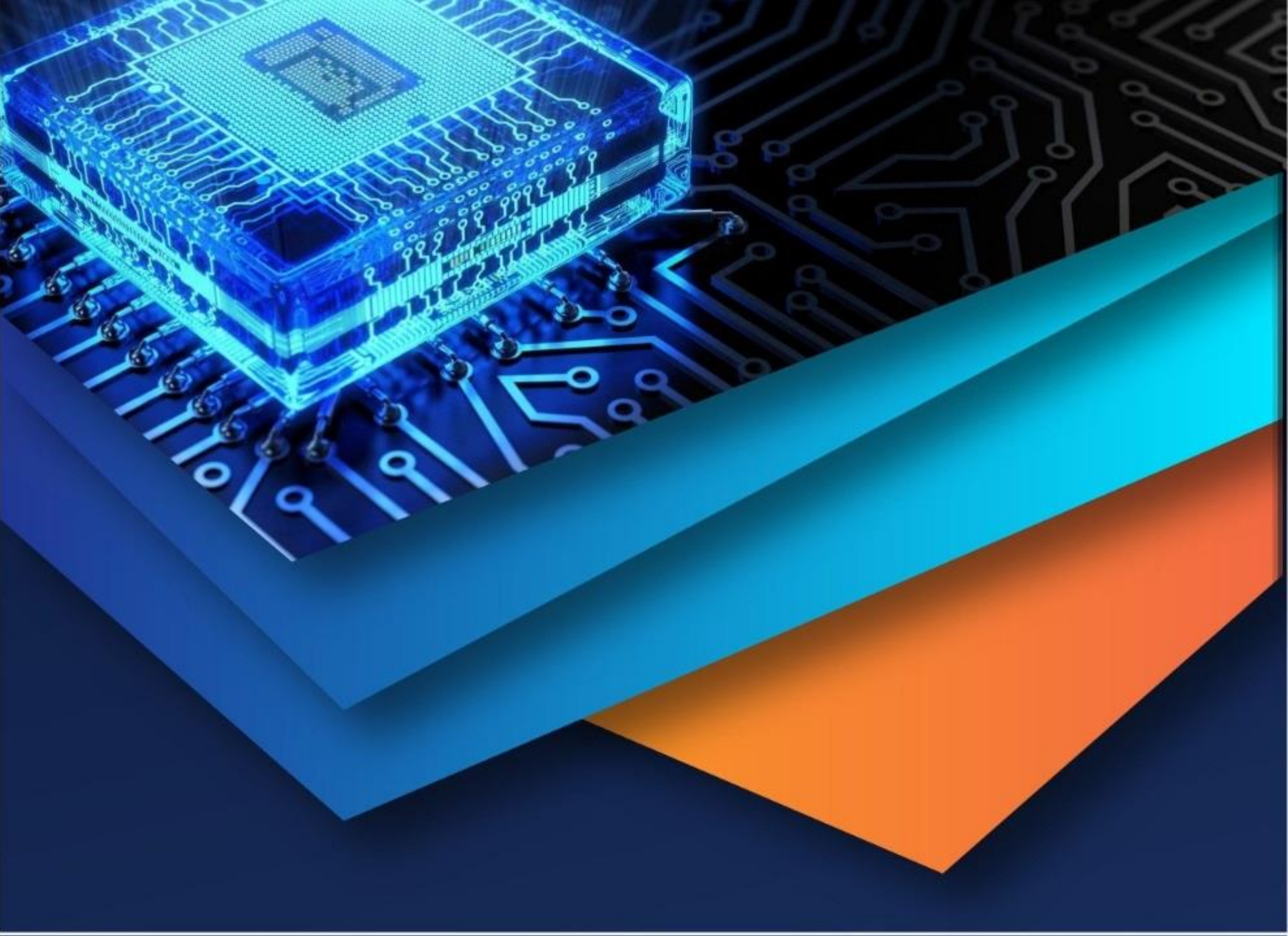

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