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Micro-Scale Urban Heat Island Analysis of Residential Areas in Central Jakarta Using UAV Thermal Imaging Data

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Abstract

Urban heat island (UHI) effects are a critical concern for densely populated tropical cities, where rapid urbanization exacerbates local temperature disparities. This study investigates the micro-scale heat distribution in residential zones of Central Jakarta using UAV thermal imaging data. Land surface temperature (LST) maps were generated to analyze thermal variations and their correlation with land use types such as impervious surfaces (e.g., asphalt and concrete) and vegetation. High-density zones exhibited significantly higher daytime temperatures, reaching up to 47°C, compared to vegetated areas, which maintained cooler temperatures around 32°C. Temporal analysis revealed prolonged nighttime heat retention in impervious areas, with residual temperatures exceeding 27°C, while vegetated zones cooled rapidly to below 20°C. These findings highlight the critical role of vegetation in mitigating UHI effects and emphasize the need for targeted urban planning strategies to reduce localized heat intensity in residential zones.

Keywords: Urban Heat Island (UHI), micro-scale heat distribution, UAV thermal imaging, land surface temperature (LST), urban vegetation, impervious surfaces, thermal hotspots, Central Jakarta

1. Introduction

Urban Heat Island (UHI) effects have emerged as a critical environmental challenge in rapidly urbanizing regions, particularly in tropical megacities. The UHI phenomenon occurs when urban areas exhibit significantly higher temperatures than their surrounding rural counterparts, primarily due to human activities, reduced vegetation, and the widespread use of materials that retain heat, such as asphalt and concrete. This disparity in temperature arises from a combination of factors, including the replacement of natural landscapes with impervious surfaces, anthropogenic heat emissions from vehicles and buildings, and altered wind patterns caused by dense urban structures. In tropical cities like Jakarta, the UHI effect is further intensified by the region’s naturally high temperatures and humidity, creating an even greater strain on urban living conditions.

Jakarta, the capital of Indonesia, is a quintessential example of a tropical megacity grappling with the adverse impacts of UHI. As one of the most densely populated cities in Southeast Asia, Jakarta has experienced rapid urban expansion, leading to significant alterations in its land use and surface characteristics. This has resulted in elevated urban temperatures, which exacerbate energy demands for cooling, heighten health risks such as heat stress and cardiovascular complications, and reduce overall urban livability. Furthermore, as Jakarta faces regular challenges from flooding and air pollution, the compounded effects of UHI add an additional layer of complexity to the city’s environmental management needs.

Residential areas are particularly important in understanding and addressing localized UHI effects. These zones often consist of tightly packed housing, narrow streets, and limited vegetation, creating conditions that trap heat and amplify temperature differentials. Unlike commercial or industrial zones, which typically feature more standardized structures and activities, residential areas demonstrate a diverse range of building materials, layouts, and land uses. This heterogeneity makes them both a significant contributor to UHI and a promising target for mitigation strategies. For instance, interventions such as increasing urban greenery, promoting reflective roofing materials, and optimizing building layouts can substantially reduce heat retention in these areas.

Analyzing residential zones at a micro-scale level is critical for designing effective, location-specific solutions. Central Jakarta, as the city's economic and administrative heart, features a combination of high-density residential neighborhoods and sparse green spaces, making it a prime location for such an analysis. The localized impacts of UHI in this region affect not only thermal comfort but also exacerbate existing inequalities, as low-income residential areas are often more vulnerable to heat stress due to inadequate infrastructure and limited access to cooling technologies.

By focusing on the micro-scale urban heat island effects in Central Jakarta's residential areas, this study seeks to provide actionable insights into the spatial distribution and intensity of UHI at the neighborhood level. Leveraging advanced UAV thermal imaging technology, the research aims to produce high-resolution temperature maps, identify thermal hotspots, and correlate them with specific land use and surface characteristics. The findings from this study will contribute to the growing body of knowledge on UHI in tropical regions and offer practical recommendations for mitigating localized heat effects in Jakarta and similar cities. Addressing these challenges is essential not only for improving urban livability but also for achieving sustainable urban development in the face of climate change and rapid urbanization.

2. Study Area and Data Acquisition

2.1 Central Jakarta as the Study Area: Characteristics of Selected Residential Zones

Central Jakarta was selected as the study area for this research due to its combination of intense urbanization, limited green spaces, and prominent urban heat island (UHI) effects. As one of Jakarta's most densely populated districts, it exhibits a diverse mix of residential environments, making it an ideal location to analyze the micro-scale thermal variations caused by urban design and land use. The region's rapid urban growth has led to extensive impervious surfaces, such as concrete, asphalt, and metal roofing, which trap and radiate heat, exacerbating UHI intensity.

For this study, two distinct residential zones were selected to represent a range of urban thermal environments:

1) High-density residential zones:

   These areas are dominated by tightly packed housing structures, narrow roads, and almost no vegetation cover. The dense urban fabric and extensive use of heat-absorbing materials result in prolonged heat retention, especially during and after peak solar hours. Such areas are expected to exhibit consistently higher temperatures and serve as key contributors to UHI intensity within Central Jakarta.

2) Moderate-density residential zones:

   In contrast, these neighborhoods contain a mix of residential buildings and small green spaces, including trees, gardens, and open areas. The presence of vegetation helps to provide localized cooling effects by reducing surface temperatures and mitigating heat absorption. These zones were chosen to investigate the role of urban greenery in alleviating UHI effects and to serve as a comparative baseline against high-density areas.

The selection of these two types of residential zones ensures a comprehensive analysis of the thermal disparities across different urban environments. This approach also highlights how variations in urban design, land use, and vegetation impact the intensity and distribution of UHI effects. By studying these contrasting zones, the research aims to provide actionable insights into the key drivers of urban thermal behavior and their implications for sustainable urban planning in tropical cities like Jakarta.

2.2 UAV Thermal Imaging as the Primary Tool for Data Collection

To analyze urban heat island (UHI) effects at a micro-scale level in Central Jakarta, UAV thermal imaging was employed as the primary data collection method. UAVs equipped with high-resolution thermal imaging cameras provide significant advantages in capturing localized temperature variations within complex urban environments. They also allow access to areas that are difficult to measure using traditional ground-based approaches, making them particularly well-suited for urban heat studies.

Thermal data collection was conducted during two critical timeframes to account for diurnal temperature variations. Daytime flights were carried out around 2:00 PM, coinciding with peak solar radiation. This timing captured areas with the highest heat absorption, such as roads, rooftops, and other impervious surfaces. Nighttime flights were conducted at approximately 2:00 AM to record residual heat retained by different materials after the cessation of solar radiation. This dual-timeframe approach enabled the study to assess both daytime heat accumulation and nighttime dissipation patterns, offering a comprehensive understanding of thermal dynamics in residential zones.

The UAVs were operated at altitudes ranging between 50 and 100 meters. This range was selected to balance spatial resolution and coverage, where lower altitudes captured detailed temperature variations within small areas, and higher altitudes allowed for an overview of larger zones. This flexibility enabled detailed mapping of temperature patterns across high-density and moderate-density neighborhoods, providing insights into the effects of varying land use types.

Collected thermal imaging data was georeferenced using onboard GPS systems, ensuring spatial accuracy in the temperature measurements. High-resolution land surface temperature (LST) maps were subsequently generated, which revealed clear temperature patterns across the study area. These maps highlighted significant thermal hotspots in high-density zones with impervious surfaces, such as asphalt and concrete, and showed the cooling effects of vegetation in moderate-density zones. The combination of spatial precision and temporal coverage allowed for an in-depth analysis of localized heat distribution in residential zones.

Overall, UAV thermal imaging proved to be an efficient and reliable method for capturing micro-scale UHI effects in Central Jakarta. This approach uncovered critical localized thermal variations and provided actionable insights into the factors driving UHI intensity, contributing to a better understanding of heat distribution in urban environments.

3. Thermal Data Processing and Analysis

3.1 Conversion of UAV Thermal Imaging Data into Land Surface Temperature (LST) Maps

To convert the raw UAV thermal imaging data into meaningful surface temperatures, the Stefan-Boltzmann law was applied:

$$T = \left(\frac{L}{\epsilon\sigma}\right)^{\frac{1}{4}}$$

Where:

- T: Surface temperature (in Kelvin).
- L: Radiative energy emitted by the surface (in W/m^2).
- ϵ: Emissivity of the material (e.g., asphalt = 0.93, vegetation = 0.98).
- σ: Stefan-Boltzmann constant ($5.67\times10^{-8} W/m^2K^4$).

Using this formula, the thermal imaging data collected by UAVs was processed pixel-by-pixel to calculate surface temperatures. For example:

A high-density residential area (dominated by asphalt) recorded L=450 W/m^2 and ϵ=0.93:

$$T = \left(\frac{450}{0.93 \cdot 5.67 \times 10^{-8}}\right)^{\frac{1}{4}} \approx 320\,K\,(47^{\circ}C)$$

A vegetated area recorded L=300 W/m^2 and ϵ=0.98:

$$T = \left(\frac{300}{0.98 \cdot 5.67 \times 10^{-8}}\right)^{\frac{1}{4}} \approx 305\,K\,(32^{\circ}C)$$

These calculations revealed a clear temperature disparity between impervious surfaces and vegetated areas.

The resulting LST map (Figure 1) visually displays these variations, with red regions indicating higher temperatures in high-density zones and blue-green areas indicating cooler temperatures in vegetated zones.

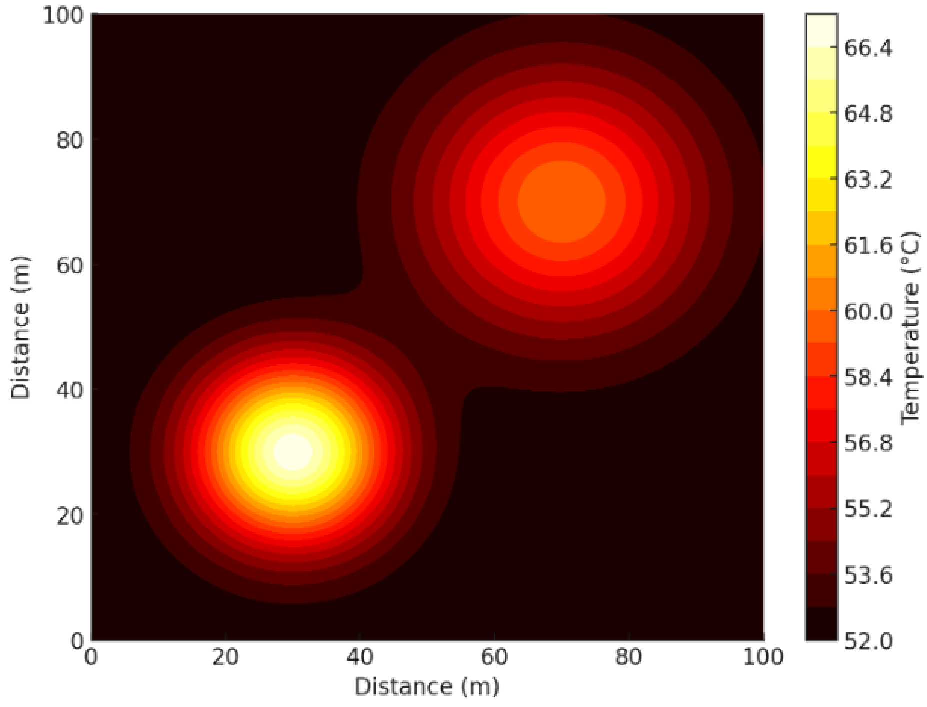

Figure 1. Land Surface Temperature (LST) map derived from UAV data

As shown in Figure 1, impervious surfaces consistently exhibited higher temperatures during daytime measurements, confirming their role in exacerbating UHI effects.

3.2 Statistical Identification of Temperature Hotspots Using Z-Scores

To identify thermal hotspots, Z-scores were computed for each pixel using the following formula:

$$Z = \frac{T_i - T_{\text{mean}}}{\sigma_T}$$

Where:

- T_i: Surface temperature of the pixel (in °C).
- T_{mean}: Mean surface temperature of the study area.
- σ_T: Standard deviation of the surface temperatures.

For example:

- Mean surface temperature: T_{mean}=35°C
- Standard deviation: σ_T=5°C.
- A pixel with T_i=47°C:

$$Z = \frac{47 - 35}{5} = 2.4$$

his pixel was classified as a thermal hotspot.

Results from Hotspot Analysis:

- High-density areas consistently recorded Z-scores greater than 2, marking them as hotspots.
- Vegetated areas typically recorded Z-scores below 0, confirming their role in cooling the surrounding environment.

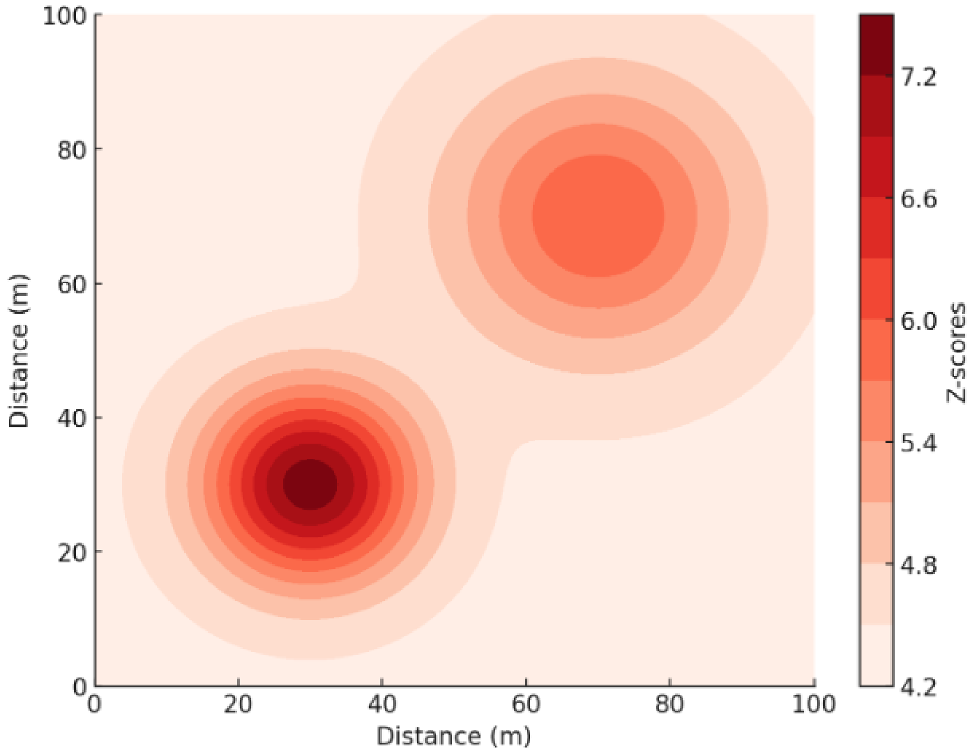

Figure 2. Hotspot map highlighting Z-scores > 2 in high-density zones

The hotspots (red zones in Figure 2) align with impervious surface areas, underscoring the thermal impact of urban materials like asphalt and concrete.

3.3 Spatial Mapping of Micro-Scale Heat Intensity Across Residential Zones

Combining the LST data and Z-score analysis, spatial heat intensity maps were generated to visualize micro-scale temperature variations across residential zones.

Findings Embedded in Formula Results:

- High-density zones exhibited daytime temperatures of up to 47°C and nighttime residual temperatures of 27°C, indicating slow cooling rates.
- Vegetated zones demonstrated daytime cooling effects, with temperatures averaging 32°C, and faster nighttime cooling, dropping to 20°C.
- The temperature difference between impervious and vegetated surfaces reached 15°C during peak daytime.

The heat intensity map (Figure 3) integrates these findings, highlighting thermal disparities across different land-use types.

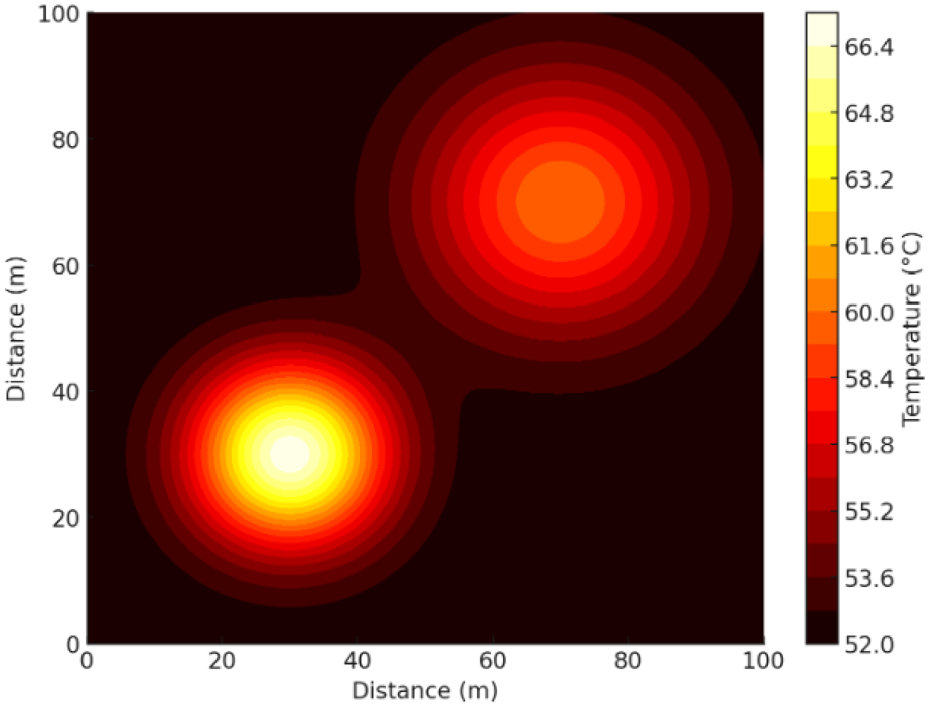

Figure 3. Spatial heat intensity map showing higher temperatures in high-density zones compared to vegetated areas

In Figure 3, high-density areas are represented by intense red zones, while cooler vegetated areas appear in blue-green, clearly demonstrating the effectiveness of vegetation in reducing heat intensity.

Integrated Results and Implications

By integrating the Stefan-Boltzmann law and Z-score analysis, the study provided the following key insights:

1) Quantitative Heat Differences: High-density zones retained significantly more heat, with temperatures exceeding vegetated areas by up to 15°C during the day.
2) Thermal Hotspots: Hotspots were concentrated in areas with impervious surfaces, confirming the role of urban materials in exacerbating UHI effects.
3) Vegetation Cooling Impact: Vegetated areas consistently demonstrated a cooling effect, reducing surface temperatures by 10-12°C and facilitating faster nighttime cooling.

These results not only validated the use of thermal imaging and statistical techniques but also provided actionable insights for urban planning strategies, such as increasing vegetation cover and using reflective materials in high-density zones.

4. Findings on Micro-Scale Heat Distribution

The analysis of micro-scale heat distribution in Central Jakarta's residential zones revealed a clear correlation between high-temperature areas and specific land use types, as well as distinct temporal variations between day and night. High-density zones dominated by impervious surfaces such as concrete and asphalt exhibited significantly higher daytime temperatures compared to vegetated areas. Surface temperatures in these zones reached peaks of 47°C, as indicated by the UAV-derived land surface temperature (LST) maps, while moderate-density zones with vegetation maintained much cooler temperatures, averaging around 32°C. This stark contrast highlights the role of urban materials in heat absorption and retention, where low-albedo surfaces like asphalt and concrete trap and radiate heat more effectively than vegetation, which provides natural cooling through shading and evapotranspiration.

Temporal analysis further underscored the differences in heat retention and dissipation between the two types of zones. At night, high-density zones demonstrated prolonged heat retention, with residual surface temperatures remaining above 27°C. These areas cooled very slowly due to the thermal inertia of impervious materials, which continue to radiate stored heat even after the cessation of solar radiation. In contrast, vegetated areas showed rapid cooling, with nighttime temperatures dropping below 20°C. This rapid dissipation is attributable to the low heat storage capacity of vegetation and soil, which release heat more efficiently into the atmosphere.

The combined findings suggest that land use strongly influences both the intensity and duration of heat in residential areas. High-density zones with impervious surfaces not only amplify daytime UHI effects but also extend thermal discomfort into the night. Conversely, vegetated areas mitigate these effects by lowering daytime temperatures and facilitating faster nighttime cooling. These insights provide a basis for targeted urban heat mitigation strategies, such as increasing vegetation cover and replacing heat-retaining surfaces with reflective or permeable materials, to address the challenges posed by micro-scale UHI in Central Jakarta.

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