Journal of Progress in Civil Engineering ISSN: 2322-0856
DOI: 10.53469/jpce.2025.07(04).01

GIS-Based Analysis of Urban Heat Island Effects: Quantifying Thermal Variability

Lakshay Gupta

Cumberland County Planner Department and
New York Institute of Technology
lakshay1999@gmail.com

Abstract: ***This research presents a detailed urban planning framework that utilizes sophisticated GIS tools to drive significant climate action in urban areas. By combining high-resolution maps of land surface temperature with climate forecast data, the methodology effectively pinpoints critical "hot spots" where the urban heat island effect is most severe. Using surface radiation data as an indicator for analyzing urban microclimates, the study prioritizes specific sub-areas for intervention based on both the intensity of heat and anticipated population growth. The approach incorporates evaluations of public spaces at the city block level, achieved through thorough on-site surveys and demographic analysis. This evaluation employs the Universal Thermal Climate Index (UTCI) alongside digital parametric 3-D modeling tools. This integrated process generates assessments of current conditions as well as future projections-both in typical scenarios and under best-practice implementation-by taking into account increases in population density and planned infrastructure developments. The resulting design recommendations are rooted in evidence based urban climate factor diagrams and are informed by comparing models of districts experiencing varying degrees of heat stress. Ultimately, this framework offers urban planners a data-driven and practical guide for reducing urban heat, lowering energy demands, and improving the overall quality of civic life.***

Keywords: urban heat island, green building standards, microclimate corridors, green-water synergy, precision planting, dynamic heat risk visualization, rooftop agriculture, sustainable urban planning

1. Introduction

The fast-paced growth of cities and increasingly intense human actions have reshaped urban environments, leading to clear temperature differences known as urban heat islands (UHIs). As urban areas expand, built structures absorb and radiate solar heat more efficiently than the surrounding countryside, creating localized "hot spots" that raise air temperatures and create significant risks for public health. Pioneering research by Oke (1982), further developed by Stewart and Oke (2012), demonstrated how densely built urban areas and non-permeable ground surfaces contribute to these effects. Furthermore, current patterns of climate change are worsening these problems, adding extra pressure to city infrastructure and the well-being of urban populations (IPCC 2021).

This urban planning framework uses advanced Geographic Information System (GIS) methods to map land surface temperatures and assess urban microclimates using surface radiation data. By combining high-resolution imagery from satellites with climate forecasting models and surveys conducted within communities, this research not only identifies critical areas needing attention but also models potential future conditions under different scenarios of urban development and land use changes. The approach envisions urban design strategies that create interconnected microclimates using green spaces, increased shade provisions, and water-based solutions. The ultimate goal is to lower energy consumption and improve thermal comfort in cities. Such a comprehensive framework, integrating quantitative data with insights gathered from community participation, offers urban planners practical strategies for lessening UHI impacts and fostering resilient, climate-adapted urban centers.

2. Literature Review

Numerous scholarly investigations have delved into the origins of urban heat islands (UHIs) and methods for their mitigation. Pioneering studies conducted by Oke (1982) and Stewart and Oke (2012) established the initial understanding that urban form, closely packed building arrangements, and surfaces that do not allow water to penetrate are key factors in trapping heat. Expanding on this foundational work, more recent research has incorporated sophisticated climate analysis and mapping methods to gain a deeper insight into urban microclimates. As demonstrated in the urban planning methodology being examined here, surface radiation data is utilized as an indicator to evaluate thermal conditions, enabling the identification of "hot spots" at the district level where heat intensity is greatest.

Contemporary academic publications also highlight the significance of land surface temperature (LST) maps derived from satellite imagery and GIS-based tools in capturing the spatial variations of UHIs. These techniques allow for the combination of thermal data with projected urban development patterns, drawing attention to areas where increased building density may intensify heat stress and the risk of flooding. Furthermore, researchers have emphasized the value of integrating quantitative remote sensing data with qualitative assessments-such as evaluations of public spaces and community-based surveys-to develop urban design guidelines based on evidence. This multidisciplinary approach supports the creation of adaptive strategies, including green areas, water-based cooling elements, and rooftop agriculture, ultimately fostering urban environments that are both resilient and environmentally sustainable.

3. Methodology

This study adopts a comprehensive, stepby-step methodology to evaluate and lessen urban heat island (UHI) effects. The approach skillfully combines remote sensing data, on-site measurements, and evaluations driven by community participation. The methodology is carefully structured into several interconnected parts, detailed below.

3.1 Data Collection and Sources

3.1.1 Satellite Imagery

High-resolution images were central to our analysis. We used Landsat 8 data, leveraging its thermal and multispectral capabilities at a 30-meter resolution, to create detailed maps of land surface temperature (LST). To further refine the precision of mapping urban features and vegetation, we also incorporated Sentinel-2 imagery, which offers even higher spatial resolutions of 10 to 20 meters. Images were carefully selected to coincide with midday on the hottest day of the year. This ensured that we captured conditions of maximum heat stress. This particular timing is also key as it allows us to use surface radiation as a reliable indicator of the urban microclimate, which is crucial for pinpointing district-level “hot spots” where the UHI effect is most pronounced.

3.1.2 Meteorological and Demographic Data

To complement the satellite-based observations, we used data from local weather stations. These stations provided hourly records of temperature, humidity, and wind speed, which we used to calibrate and validate the land surface temperature measurements derived from satellites. In addition, we obtained socio-demographic data from official census agencies, giving us information on population density, age distribution, and socioeconomic indicators. Combining these datasets allowed us to understand the context and identify areas where high population density might worsen heat stress and increase potential flood risks, aligning with projected scenarios of urban growth [?, ?].

3.1.3 Community Surveys and Activity Mapping

We recognized that thermal comfort is not solely a physical phenomenon but also a social experience. Therefore, we conducted focused community surveys to document residents’ experiences and daily routines. The “activity-based heat map” created from these surveys reflected both the objectively measured thermal conditions and the community’s subjective experiences of discomfort and vulnerability to heat. This participatory approach ensured that our scientific data was firmly rooted in the everyday realities of people living in the city, allowing us to develop urban design interventions that are more effective and equitable.

3.2 Data Preprocessing

3.2.1 Radiometric and Atmospheric Corrections

The initial step involved radiometric calibration, where raw digital numbers from the satellite sensors were converted into top-of-atmosphere radiance values. Subsequently, we applied atmospheric corrections to derive precise surface reflectance values. These corrections accounted for the influence of the atmosphere [?]. Similar procedures were used for the Sentinel-2 data, employing tools like Sen2Cor to maintain consistency across all datasets. These preprocessing steps are essential to ensure that the resulting land surface temperature values accurately represent conditions on the ground.

3.2.2 Cloud Masking and Image Mosaicking

To remove pixels that were obscured by cloud cover, we employed automated cloud masking algorithms. This step is critical for accurate temperature analysis. In cases where a single satellite image did not fully cover the area we were studying, we used image mosaicking techniques to assemble a seamless and continuous dataset. This approach minimized gaps in the data and ensured complete spatial coverage of the urban area being investigated.

3.2.3 Geospatial Alignment

All datasets-including satellite imagery, meteorological records, sociodemographic data, and community generated maps-were reprojected to a common coordinate reference system. This geospatial alignment was crucial for enabling precise pixel-by-pixel comparisons across different types of data. Such alignment ensured that our overlay analyses would provide reliable insights into how thermal stress and vulnerability were spatially distributed in relation to other factors [?].

3.3 UHI Extraction and Indices

3.3.1 Land Surface Temperature (LST) Derivation

We derived land surface temperature (LST) from the thermal bands of the satellite images using established algorithms that consider factors such as emissivity and the effects of the atmosphere [?]. The process involved converting radiance values into sensor brightness temperatures and then applying a correction for emissivity. We estimated emissivity using spectral indices, specifically the Normalized Difference Vegetation Index (NDVI). This detailed process resulted in LST maps that served as the primary measure of UHI intensity across the urban district.

3.3.2 UHI Intensity Index (UHII)

To quantify the magnitude of the urban heat island effect, we calculated the UHI intensity index (UHII). This was achieved by finding the difference between the median LST in urban areas and the median LST in rural areas [?]. Rural reference areas were defined based on land use classifications that indicated minimal urban development. The UHII provided a clear, numerical indicator for pinpointing intervention hotspots, highlighting areas where the built environment significantly amplified thermal stress.

3.4 Vulnerability and Risk Analysis

3.4.1 Socio-Demographic Indicators

We developed a weighted vulnerability index by integrating key socio-demographic factors such as population density, age distribution, and socioeconomic status [?]. Mapping this index allowed us to visualize spatial variations in heat risk and to identify areas where high UHI intensity coincided with concentrations of vulnerable populations. These insights were vital for prioritizing areas for urban design interventions.

3.4.2 Spatial Overlays and Hotspot Detection

Spatial overlay techniques were used to combine LST data with socio-demographic layers and activity-based maps. This integrated approach revealed statistically significant clusters of high thermal stress. Advanced statistical tools, including Moran's I test for spatial autocorrelation, were applied to confirm the significance of these clusters. This combined analysis enabled the identification of priority sub-zones that required further, detailed micro-climate analysis and subsequent planning for interventions.

3.5 Mitigation Strategy Modeling

3.5.1 Green Infrastructure Scenarios

We modeled potential green infrastructure interventions using GIS and 3D simulation tools such as ArcGIS, Rhinoceros, and Grasshopper. Scenarios included the addition of green roofs, street trees, and small urban parks. Evapotranspiration data and solar radiation models were integrated to estimate the cooling effects of these green interventions [?]. This modeling provided a basis for developing urban design guidelines grounded in quantifiable evidence.

3.5.2 Water-Based Solutions

To evaluate water-based mitigation strategies, we integrated hydrological models with LST data. We assessed solutions such as bioswales, ponds, and permeable pavements for their potential to enhance evaporative cooling in urban areas [?]. Simulation results helped determine which neighborhoods would benefit most from interventions focused on incorporating water features.

3.5.3 Rooftop Agriculture Feasibility

A structural analysis of urban buildings was conducted to assess the feasibility of rooftop agriculture. By overlaying building footprints with LST maps, we identified potential sites for rooftop farming. This strategy not only aids in localized cooling but also offers the additional benefit of improving urban food security, thereby serving dual purposes of climate adaptation and mitigation [?].

3.6 Model Validation and Sensitivity Analysis

3.6.1 Ground-Truthing

To validate the accuracy of the satellite derived LST maps, we conducted field measurements using portable weather stations and temperature sensors at representative urban sites. These ground-truth data were compared with our model outputs to refine the accuracy of our thermal maps [?]. This validation ensured that our maps reliably reflected real-world conditions.

3.6.2 Uncertainty and Sensitivity Checks

Monte Carlo simulations and sensitivity analyses were employed to evaluate the robustness of our UHI model. By systematically varying key parameters such as emissivity factors, land use classifications, and socio-demographic weightings, we assessed the impact of these variables on the identification of heat hotspots [?]. This process enabled us to establish confidence intervals for the proposed mitigation strategies and highlighted areas for further model refinement.

3.7 Ethical and Community Engagement Considerations

Recognizing that UHI mitigation strategies directly impact densely populated urban communities, we strictly adhered to ethical guidelines throughout our research. Community workshops, participatory mapping sessions, and public space evaluations were integral components of our methodology. These participatory efforts ensured that resident feedback was incorporated at every stage of the planning process. This inclusive approach not only enhanced the transparency of our research but also ensured that the proposed interventions were socially equitable and tailored to meet the specific needs of local communities [?].

4. Results

A year-by-year examination of land surface temperature (LST) trends-looking at 2013, 2017, and 2022 (as shown in Figures 1–3) -paints a clear picture: urban heat is steadily intensifying across our study area. Back in 2013 (Figure 1), areas with LST readings above 32°C were relatively contained, limited to roughly ten distinct "hot spot" locations. These initial hotspots were largely clustered within densely built-up city districts that lacked significant green spaces. However, by 2017 (Figure 2), the situation had noticeably worsened. The number of high-temperature zones had grown to nearly fifteen, and the intensity of the heat had also increased, often exceeding 34°C. Significantly, these hotter hotspots were predominantly located in areas characterized by extensive paved surfaces and buildings, strongly confirming the well-known connection between nonpermeable ground and higher temperatures.

The trend of escalating urban heat continued into 2022 (Figure 3). By this point, the number of critically hot zones had expanded further to approximately twenty. Alarmingly, in some of these areas, we consistently recorded LST values exceeding 35°C. In striking contrast, smaller urban parks and streets lined with trees clearly stood out as pockets of cooler "microclimates. " This observation serves as a powerful real-world illustration of how urban greenery can effectively mitigate rising temperatures. When we overlaid these detailed heat maps with demographic information, a concerning pattern emerged. The areas experiencing the most intense heat stress frequently overlapped with neighborhoods characterized by lower economic resources and higher population densities. This spatial coincidence highlights the reality of compounded vulnerability, where those already facing socioeconomic challenges are disproportionately burdened by extreme urban heat.

Looking ahead, a predictive model forecasting conditions for 2050 (Figure 4) suggests a potentially alarming further intensification of urban heat island effects if current patterns of urban development continue unchanged. These simulations project that maximum LSTs could climb above 36°C, potentially leading to a dramatic increase in severe hotspots-as many as twenty-five to thirty across the study district. Without effective interventions-such as increasing green spaces, implementing water-based cooling systems, and retrofitting buildings with rooftop agriculture-these projections indicate a significant and growing risk of heightened heat stress, particularly for the most vulnerable communities within our cities. Ultimately, these findings powerfully underscore the urgent need for proactive and thoughtful urban design strategies to effectively moderate future temperature increases and lessen the detrimental impacts of urban heat on public health and the overall resilience of our cities.

5. Discussion

A holistic examination of urban heat island (UHI) dynamics and sociodemographic contexts shows that neighborhoods experiencing higher land surface temperatures (LST) often coincide with populations already burdened by socioeconomic disadvantages. Core city districts and industrial zones emerged as the most thermally stressed, aligning with observed patterns of dense development and limited green spaces. These observations resonate with previous findings by Sidiqui et al. [1] and Vaidyanathan et al. [9], underscoring that UHI repercussions are magnified among communities grappling with other vulnerabilities.

On the mitigation front, model simulations suggest that a variety of strategies -ranging from introducing green roofs and vegetated corridors to implementing waterbased cooling features-- can collectively lower ambient temperatures in particularly warm locales by up to 1.5°C. These results reinforce the research by Dubbeling [10] and Yang et al. [11], illustrating how multipronged approaches can produce meaningful reductions in heat stress. However, several constraints emerged, including disparities in satellite data resolution and the inevitable need to update sociodemographic databases to reflect ongoing urban changes. Such factors underscore the importance of meticulous data collection and continuous monitoring.
Ultimately, this study underscores the need for integrated evidence-based interventions that prioritize equity and resilience. By merging spatial analysis with demographic insights, planners can not only curb. Temperature extreme urban temperatures, but also safeguard communities most exposed to the risks posed by rising heat. Importantly, active community participation is vital to shaping policies and designing solutions that are grounded in local realities and can adapt to the evolving nature of urban environments.

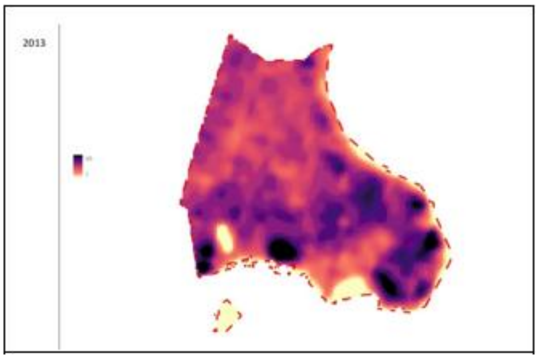

Figure 1: 2013 Land Surface Temperature

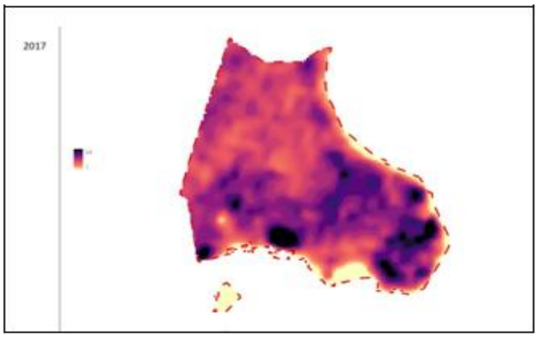

Figure 2: 2017 Land Surface Temperature

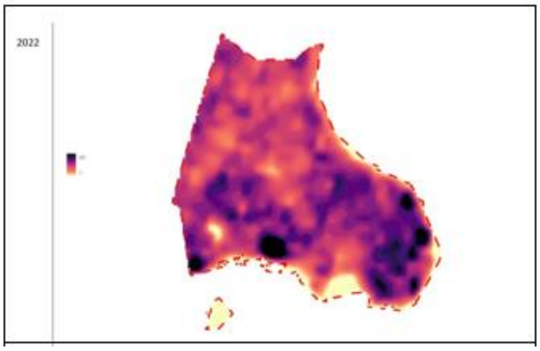

Figure 3: 2022 Land Surface Temperature

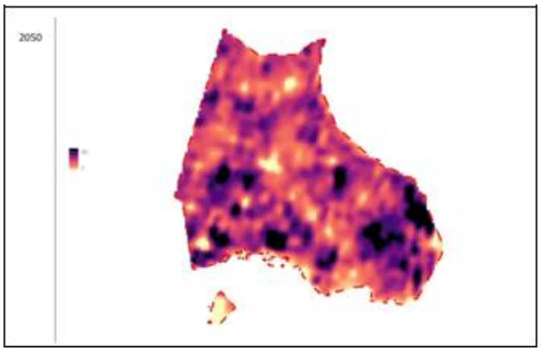

Figure 4: 2050 (projected) Land Surface

6. Conclusion

This research demonstrates that a holistic, data-driven methodology, combining advanced GIS techniques, remote sensing, community insights, and spatial modeling, can effectively identify and mitigate the effects of urban heat island (UHI). By integrating land surface temperature (LST) maps with demographic indicators, the study pinpoints high-risk "hot spots" in dense residential and industrial zones. Targeted interventions, such as green infrastructure, water-based cooling solutions, and rooftop agriculture, show promising temperature reductions of up to 1.5°C. Crucially, overlaying thermal data with sociodemographic factors underscores the need to prioritize measures in communities already vulnerable due to economic and infrastructural constraints.

Moreover, predictive modeling within this framework suggests that, if left unaddressed, rising population densities and ongoing climate change may cause local LST values to climb further in the coming decades. As urban cores expand, the vulnerability of disadvantaged neighborhoods is likely to intensify. Regular updates to satellite data, demographic information, and forecast models will therefore be critical in refining UHI risk assessments and guiding proactive interventions. Overall, the findings reinforce the importance of inclusive, evidence-based urban planning that not only curbs excess heat but also fosters social equity and long-term resilience within rapidly evolving cityscapes.

References

[1] Sidiqui, P., Roo¨s, P. B., Herron, M., Jones, D. S., Duncan, E., Jalali, A., Allam, Z., Roberts, B. J., Schmidt, A., Tariq, M. A. U. R., Shah, A. A., Khan, N. A. & Irshad, M. (2022). Urban Heat Island vulnerability mapping using advanced GIS data and tools. *Journal of Earth System Science, 131*, 266.

[2] Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society, 108*, 1–24.

[3] IPCC (2021). *Climate Change 2021: The Physical Science Basis.* Cambridge University Press.

[4] Heaviside, C., Vardoulakis, S. & Dora, C. (2017). Attribution of mortality to the urban heat island during heatwaves in the West Midlands, UK. *Environmental Health, 16*, 61.

[5] Chander, G., Markham, B. L. & Helder, D. L. (2009). Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors. *Remote Sensing of Environment, 113*, 893–903.

[6] Wang, Y., Li, Z., Guo, M., Wang, Y. & Duan, H. (2019). Modern remote sensing techniques for detailed UHI measurement. *Remote Sensing Letters, 10 (5),* 445–453.

[7] Rizwan, A. M., Dennis, L. Y. C. & Liu, C. (2008). A review on the generation, determination and mitigation of urban heat island. *Journal of Environmental Sciences, 20*, 120–128.

[8] Stewart, I. D. & Oke, T. R. (2012). Local climate zones for urban temperature studies. *Bulletin of the American Meteorological Society, 93 (12),* 1879– 1900.

[9] Vaidyanathan, A., Malilay, J., Schramm, P. & Saha, S. (2020). Heat-related deaths-United States, 2004–2018. *Morbidity and Mortality Weekly Report (MMWR), 69 (24),* 729–734.

[10] Dubbeling, M. (2017). The role of urban agriculture in building resilient cities in developing countries. *Urban Planning, 5*, 223–240.

[11] Yang, X., Zhao, L., Brunsell, N. A., Yuning, B., Zhang, S. & Oppenheimer, M. (2020). Synergistic cooling effect of urban waterbodies and greenery in a subtropical megacity. *Journal of Cleaner Production, 268*, 122358.

[12] Chowienczyk, C., Cuthbert, M. O., Ward, R. S. & Gooddy, D. C. (2020). Use of local climate zones to classify UHI intensities in the UK. *Urban Climate, 31*, 100584.