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Evaluating the Cooling Efficacy of Urban Cool Islands (UCIs) in Secondary Tropical Cities: A Microclimatic Analysis of Rajshahi, Bangladesh

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Abstract

Rapid urbanization in Rajshahi has intensified Urban Heat Island (UHI) effect, while the cooling performance of urban blue infrastructure remains insufficiently understood. This study evaluates the cooling efficacy of the Padma River and urban ponds through satellite-derived Land Surface Temperature (LST), morphological analysis, land cover interaction, and microclimatic profiling. Landsat 9 thermal data and ESA WorldCover datasets were integrated within a GIS framework to quantify Urban Heat Island Intensity (UHII) between Rajshahi City Corporation (RCC) and surrounding Paba Upazila. Results show a mean UHII of 0.41°C, with localized extremes exceeding ±8°C. The Padma River functioned as the primary macro-scale cooling sink, extending cooling up to 1.7 km through open morphologies, while dense compact zones restricted penetration below 700 m. Large compact ponds produced the strongest localized cooling ($\Delta T \approx 6.9$°C), whereas interconnected small ponds stabilized urban thermal variance. The study demonstrates that blue infrastructure morphology and adjacent land cover critically regulate urban thermal resilience.

Keywords: Urban Heat Island (UHI); Urban Cool Island (UCI); Cooling Effect; Blue Infrastructure, Land Surface Temperature (LST).

1. Introduction

Global climate change, coupled with rapid urbanization, has significantly intensified urban thermal stress, particularly in the rapidly growing secondary cities of the Global South. Rajshahi, a key secondary city in subtropical Bangladesh, has experienced an extensive transformation of natural surfaces into built-up and heat-absorbing land covers, contributing to a modified surface energy balance and heightened thermal discomfort. Traditional urban climate scholarship has long established the correlation between impervious surfaces and rising Land Surface Temperature (LST). In response, the concept of "Blue Infrastructure" (BI)—encompassing rivers, wetlands, and ponds—has emerged as a vital tool for creating Urban Cool Islands (UCIs) that provide localized relief (Stewart & Oke, 2012). Remote sensing has become central to this field, as satellite derived LST enables a spatially continuous assessment of surface thermal variation across large areas (de Almeida et al., 2021; Shi et al., 2021). However, while LST-based studies have advanced the mapping of urban heat patterns, methodological approaches remain uneven, particularly in the selection of rural baselines and the integration of morphological indicators (Gupta et al., 2019).

Within this scholarship, water bodies reduce surrounding temperatures through evaporative cooling and high heat capacity (Gunawardena et al., 2017; Jandaghian & Colombo, 2024). Studies show that the thermal effect of water bodies depends on size, depth, and surrounding land use (Peng et al., 2020). Larger water bodies often provide stronger cooling because of their thermal inertia, though stored heat may be released gradually, making effects variable across the diurnal cycle. Smaller ponds, although limited in cooling depth, may still play an important role in dense urban fabrics by interrupting continuous heat accumulation and producing localized relief. Recent research also challenges the assumption that UCI performance is simply a function of size. Peng et al. (2020) identify "patch size thresholds," suggesting that beyond a certain point, additional area produces diminishing marginal cooling benefits. This shifts attention toward morphology and spatial configuration. Landscape metrics such as compactness and shape complexity influence how a water body interacts with its surrounding fabric (Yang et al., 2015). Compact water bodies may preserve a stronger internal "cool core," while irregular features with greater edge exposure may be more vulnerable to surrounding impervious heat.

The effectiveness of blue infrastructure is further shaped by the land-water interface. Green and blue spaces can produce synergistic cooling when water bodies are combined with tree canopies and airflow corridors (Han et al., 2022). Conversely, the interface condition is critical for riverine cities where the cooling potential of a major water body may not automatically penetrate the urban core. Building on this, the present study frames surrounding land covers as potential "Thermal Bridges" when vegetated areas help transfer cooling inland, and "Thermal Barriers" when compact built-up or barren surfaces obstruct the cooling gradient. In Rajshahi, this is exemplified by the "chars"—large, unshaded sandbars in the riverbed. These dry, sandy surfaces exhibit extremely high LST, effectively acting as "heat walls" that choke the river's cool breeze before it can reach the residential fabric.

Despite growing scholarship, three unresolved gaps remain particularly relevant. Theoretically, there is limited explanation of how the geometry of blue infrastructure—specifically compactness and networked distribution—conditions the spatial extent and magnitude of cooling. Methodologically, while broad LST-NDVI correlations identify where heat exists, they often fail to explain the spatial mechanics of cooling reach—specifically why relief "chokes" at certain interfaces. Empirically, Rajshahi serves as a representative morphological case for secondary tropical cities, containing a complex thermal landscape of riverine edges, sand-covered chars, and institutional "bridges" that have not been synthesized into a single performance-based framework. This study moves beyond the question of if water cools a city and instead examines how its morphology determines where and how far cooling is transferred through the fabric.

In response to these gaps, this study asks three interrelated research questions. First, what is the magnitude of Urban Heat Island Intensity in Rajshahi when the urban core is measured against a rural baseline, and where are the major thermal nodes located? Second, to what extent do the area and compactness of urban ponds determine the depth and spatial reach of their cooling effects? Third, how do different land-cover interfaces, particularly the barren chars and vegetated institutional zones, influence the penetration of cooling from the Padma River into the city? Accordingly, the aim of this study is to evaluate the cooling efficacy of Rajshahi's blue infrastructure by examining the relationship between morphology, land-cover interfaces, and urban thermal regulation. The specific objectives are to quantify UHII through a comparison between Rajshahi City Corporation and Paba Upazila, classify thermal zones using a standard-deviation-based framework, model the cooling intensity of different water-body typologies, and identify how surrounding land covers function as either thermal barriers or bridges.

This research moves UHI discourse beyond descriptive mapping toward an explanation of the spatial mechanisms that produce urban cooling. If water bodies are assessed only by presence or total area, planning decisions may overlook the importance of compactness and connectivity. By integrating satellite derived LST, morphological analysis, and microclimatic profiling, this study advances understanding of how blue infrastructure performs as a thermal regulation system. It offers planning-relevant insights for protecting compact ponds and managing barren or sandy interfaces to improve heat resilience in Rajshahi and comparable tropical urban contexts.

2. Materials and Methods

The analytical framework of this study integrates satellite remote sensing, spatial morphological metrics, and microclimatic gradient profiling to evaluate the Urban Heat Island (UHI) intensity and Urban Cool Island (UCI) efficacy in Rajshahi.

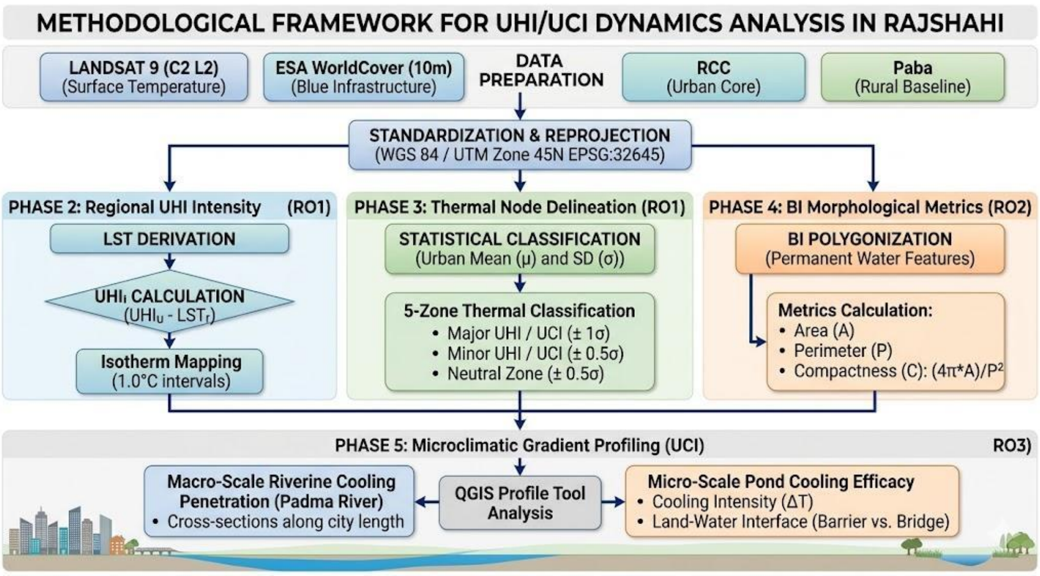

Figure 1. Methodological workflow illustrating the integration of satellite-derived thermal data, land-cover classification, morphological metric calculation, and microclimatic profiling.

The workflow is designed to move beyond descriptive mapping by linking Land Surface Temperature (LST) patterns with the geometric "shape resilience" of blue infrastructure and the regulatory role of the land-water interface. The research was executed in five integrated stages: data acquisition and geometric standardization, regional thermal baseline construction, statistical UHI/UCI zoning, morphological analysis of water bodies, and profile-based cooling-gradient assessment.

2.1 Study Areas

Rajshahi is a major secondary city in northwestern Bangladesh and the administrative headquarters of the Rajshahi District. Geographically, the city is situated on the northern bank of the Padma River, forming a critical urban node at the intersection of the Barind Tract and the river's alluvial plains.

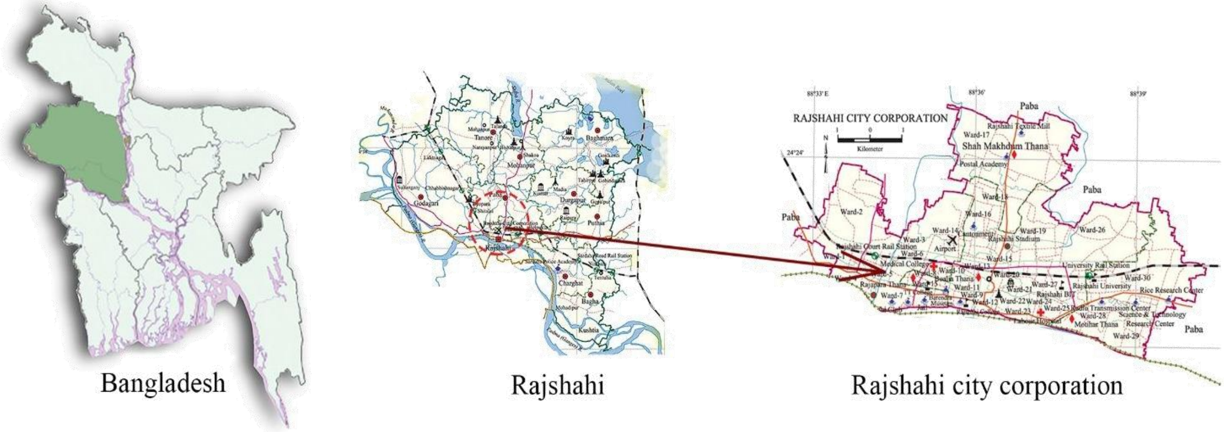

Figure 2. Location of the study area showing Bangladesh, Rajshahi District, and the boundary of Rajshahi City Corporation (RCC), selected as the urban core for UHI/UCI analysis. (Developed by the Authors).

The Rajshahi City Corporation (RCC) lies between 24°20′–24°24′ N latitude and 88°32′–88°40′ E longitude. While the official administrative boundary of RCC covers approximately 95.56 km², this research utilizes a processed analytical sample area of 47.06 km² to ensure high-resolution data consistency. The city is bounded on all sides by the Paba Upazila (340.03 km²), which serves as the rural reference landscape for thermal comparison (Figure 2). Paba is characterized by lower-density settlements and agricultural land uses, bounded by the Upazilas of Mohanpur and Tanore to the north, Puthia and Durgapur to the east, and Godagari to the west.

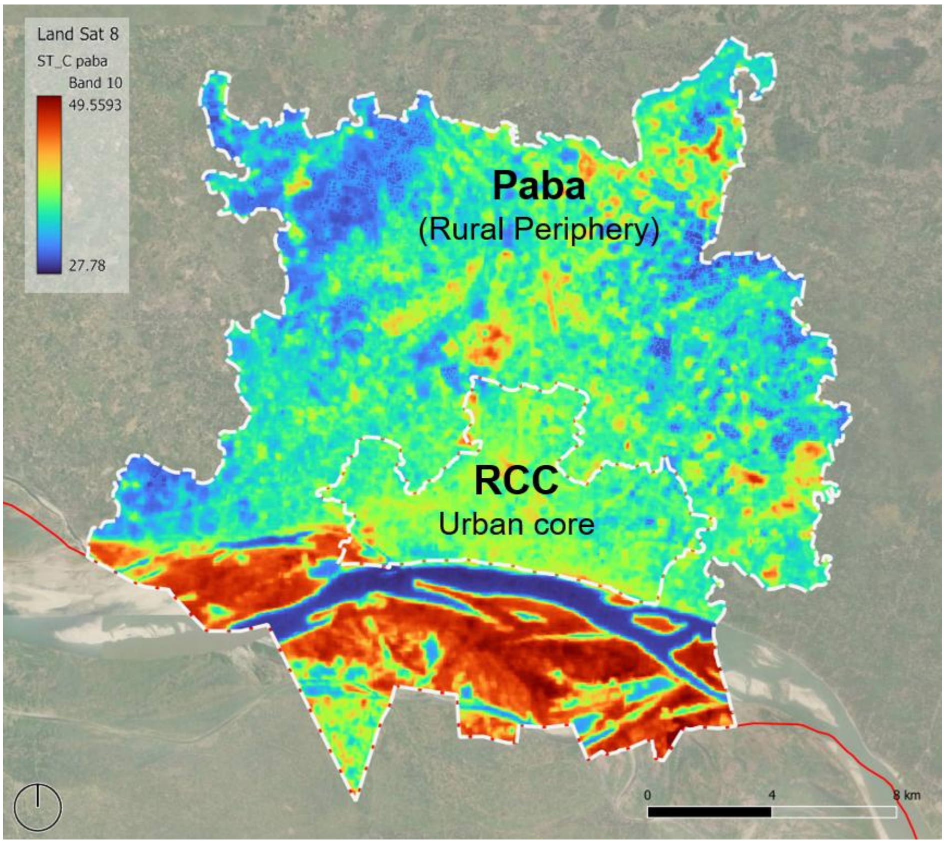

Figure 3. Land Surface Temperature (LST) gradient map illustrating thermal variation across Paba Upazila and Rajshahi City Corporation (RCC) as the selected urban core.

The region experiences a Tropical Savanna climate (Aw) under the Köppen-Geiger classification, characterized by a monsoon-influenced cycle with high summer temperatures and distinct wet and dry periods. While Bangladesh is broadly humid, Rajshahi is part of the western dry zone, receiving a relatively lower annual rainfall of approximately 1,500–1,600 mm (Figure 4). The hot season extends from March to July, with recent peak temperatures reaching 39.5°C, making it an ideal period for examining extreme heat accumulation. This climatic context, coupled with the red-clay soil characteristics of the adjacent Barind Tract, creates a unique thermal environment where surface modification leads to significant radiative heat absorption.

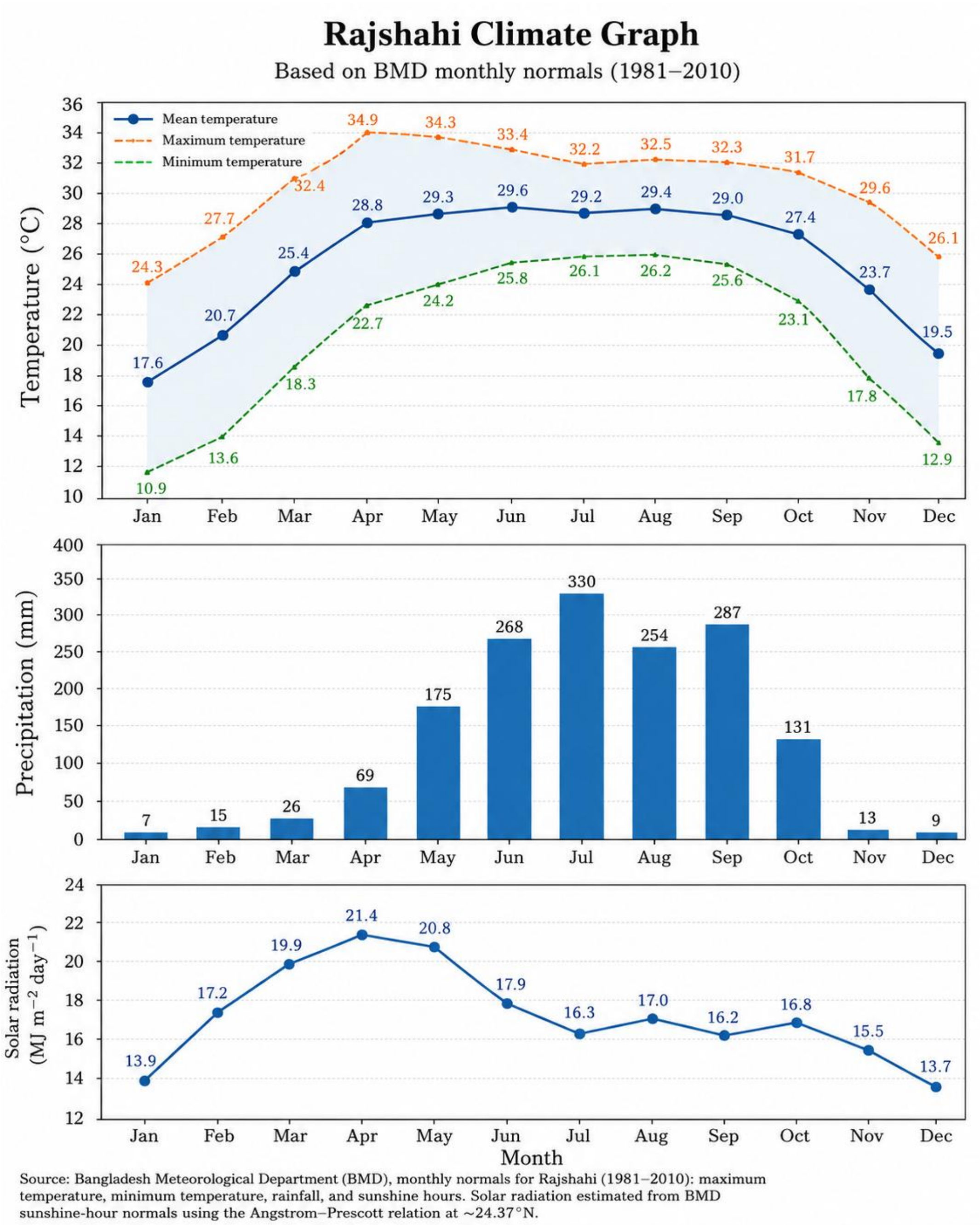

Figure 4. Monthly climate profile of Rajshahi showing temperature, precipitation, and estimated solar radiation based on BMD monthly normals for 1981–2010.

The Padma River, a major transboundary distributary, flows along the southern edge of the city and acts as the primary macro-scale Urban Cool Island (UCI). This riverine infrastructure is supplemented by a network of internal urban ponds and heritage dighis scattered throughout the urban fabric. To quantify urban–rural thermal divergence, the study compares the LST characteristics of Rajshahi City Corporation (RCC), representing the urban core, with the surrounding Paba Upazila, which serves as the rural/peri-urban baseline within the same spatial frame (Figure 3). Statistical analysis reveals that while the urban core is trapped in a uniform "heat plateau" (Mean LST: 37.41°C, SD: 1.86), the rural periphery remains thermally diverse (Median LST: 35.95°C, SD: 4.8). This setting provides a robust laboratory for evaluating how both macro-scale riverine cooling and micro-scale pond-based geometry regulate temperatures across a secondary tropical city.

2.2 Data Acquisition and Coordinate Standardization

Multi-source geospatial datasets were utilized to quantify the thermal structure of Rajshahi. Surface temperature was derived from Landsat 9 (Collection 2, Level 2) products, selected for their superior radiometric resolution and atmospherically corrected LST values. Land-cover identification was based on ESA WorldCover 10m data (Figure 5), which provided the high spatial resolution necessary to isolate small-scale urban ponds and distinguish permanent water bodies from seasonal wetlands.

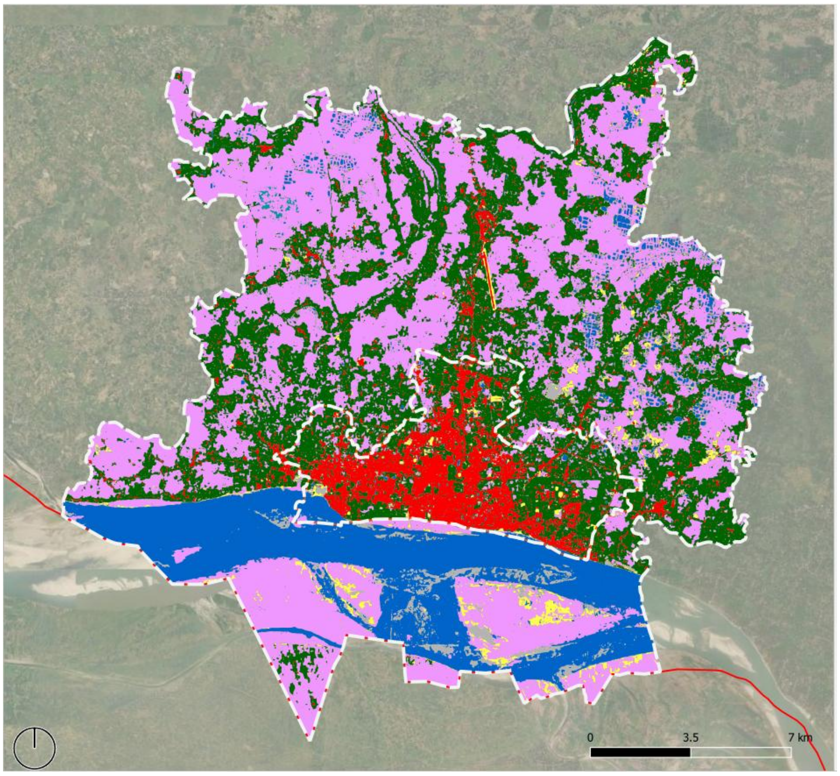

Figure 5. High-resolution Land Use and Land Cover (LULC) map of the study area (ESA WorldCover 10m), depicting the Rajshahi City Corporation (RCC) urban core nested within the larger rural Paba Upazila baseline. The map follows official ESA palette, highlighting tree cover (Value 10, Dark green), permanent water (Value 80, Blue), built-up (Value 50, red), cropland (Value 40, yellow/tan), bare soil (Value 60, Violet) .

To ensure geometric consistency, all raster and vector datasets were reprojected into the WGS 84 / UTM Zone 45N coordinate system (EPSG:32645). This projection was selected because it supports accurate metric measurements of distance, area, and perimeter, which are essential for profile-based cooling analysis and morphological assessment of water bodies. For regional comparison, the Rajshahi City Corporation (RCC) boundary represented the urban core, while the surrounding Paba Upazila provided the rural/peri-urban reference baseline.

2.3 Regional Thermal Baseline and UHII Calculation

The regional Urban Heat Island Intensity (UHII) was quantified using a dual-scale framework. RCC was treated as the urban thermal unit, characterized by compact built-up and heat-absorbing surfaces, while Paba was utilized as the rural baseline due to its high proportion of agricultural land and lower-density fabric. Mean LST values for both zones were extracted using zonal statistics. and the regional UHII was computed as the mathematical divergence between these means, yielding a city-wide intensity value of 0.41°C.

$$UHII_{(i,j)} = LST_{(i,j)} - LST_{rural\_mean}$$

Equation 1. Pixel-level calculation of UHII, where $LST_{(i,j)}$ represents the temperature at a specific spatial coordinate (i,j) and LST_{rural_mean} is the constant mean temperature of the rural reference area.

To move beyond a single descriptive metric and visualize internal thermal variations, this study establishes a pixel-wise Urban Heat Island Intensity (UHII) model. The Land Surface Temperature (LST) of the high-density urban core (RCC) was compared against the mean thermal state of the rural baseline (Paba). The UHII for every individual pixel within the urban study area was derived by subtracting the rural mean LST_{rural_mean} from the local urban pixel value $LST_{(i,j)}$, as defined in Equation 1.

This spatial derivation allows for a normalized thermal landscape where the "Zero" baseline represents the average rural condition. Areas where UHII > 0 represent heat-island conditions, while negative values (UHII < 0) indicate localized cool islands. This transformation was essential for generating the isotherm contours and the five-zone statistical model, as it filters out the regional background temperature and highlights only the intensity of local anomalies.

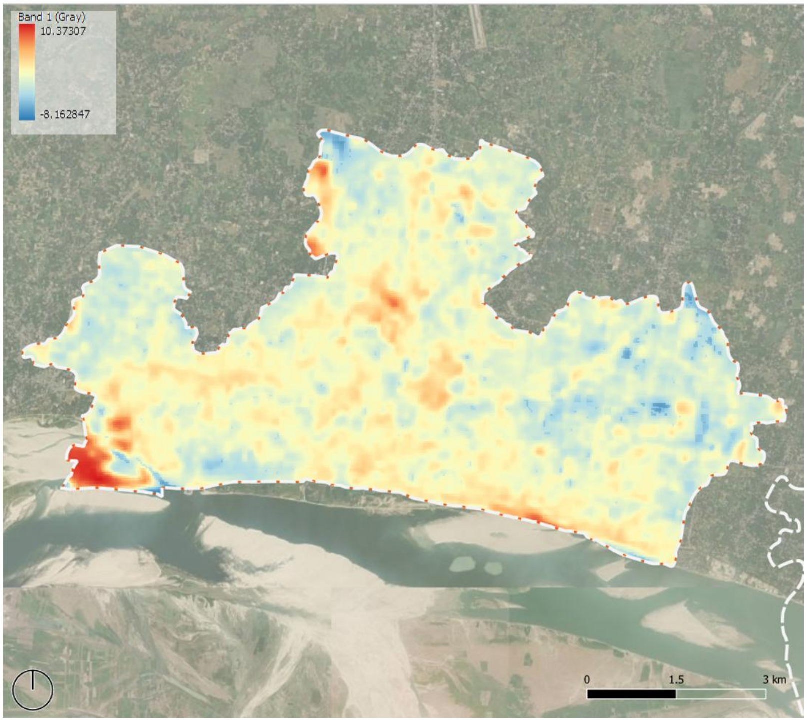

Figure 6. Urban Heat Island Intensity (UHII) gradient across Rajshahi City Corporation. The map illustrates a total thermal range of 18.53°C, with intensities peaking at +10.37°C in high-albedo industrial areas and barren soil and dropping to -8.16°C within the Padma River cooling corridor and in the pond areas.

2.4 Statistical Delineation of Thermal Nodes

To isolate actionable areas of heat stress and cooling relief, a 5-Zone statistical model was developed based on the RCC temperature distribution. Rather than employing arbitrary temperature cut-offs, this model utilized the urban LST mean (μ) and standard deviation (σ) to define objective boundaries. This approach filters out temporary spot anomalies while highlighting neighborhood-scale thermal trends.

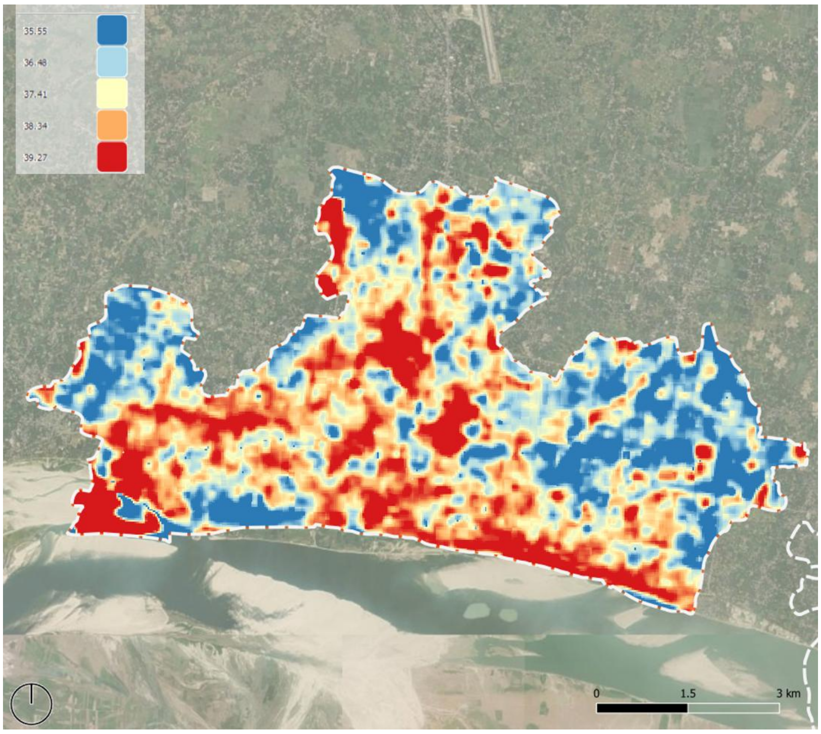

Figure 7. Thermal Node Mapping of Rajshahi. A 5-class statistical model delineating heat accumulation (Red/Orange) and cooling relief (Blue/light blue) zones based on the urban mean temperature (μ = 37.41ºC) distribution and standard deviation (σ = 1.86ºC).

Table 1. Standard-deviation-based classification of thermal zones from Major UCI to Major UHI, where μ is the mean urban LST and σ is the standard deviation of urban LST.

Zone Category	Classification	Temperature Threshold (°C)
Major UCI	LST<μ−σ	< 35.55
Minor UCI	μ−σ≤LST<μ−0.5σ	35.55 - 36.48
Neutral Zone	μ−0.5σ≤LST≤μ+0.5σ	36.48 - 38.34
Minor UHI	μ+0.5σ<LST≤μ+σ	38.34 - 39.27
Major UHI	LST>μ+σ	> 39.27

The classification logic is defined in Table 1, delineating the landscape into Major UCI, Minor UCI, Neutral Zone, Minor UHI, and Major UHI. This tiered framework provided the mathematical basis for identifying how blue infrastructure interrupts the dominant urban thermal background. This classification was used to distinguish extreme cooling nodes, moderate cooling zones, the normal urban thermal background, emerging heat anomalies, and major heat-stress zones. The resulting thermal-zone map provided the basis for identifying where blue infrastructure interrupts or moderates the city's heat pattern.

2.5 Morphological Analysis of Blue Infrastructure (BI)

To evaluate how the geometry of blue infrastructure influences cooling efficacy, permanent water bodies were extracted and polygonized from the land-cover dataset. The Padma River and selected urban ponds were analyzed as distinct blue-infrastructure typologies. For each water body, area (A), perimeter (P), and compactness (C) were calculated. Area indicates the spatial extent of the water body, while perimeter captures the length of the land-water interface. Compactness was used to assess the regularity of water-body shape and its potential to preserve a stable internal cooling core. Compactness was calculated using Equation 2.

$$C = \frac{4\pi A}{P^2}$$

Equation 2. Compactness index of blue infrastructure, where A is the area and P is the perimeter of the water body; values closer to 1.0 indicate a more compact or circular form.

A compactness value close to 1.0 represents a near-circular or regular shape, while lower values indicate irregular, elongated, or fragmented forms. This metric allowed comparison between different water-body typologies, including large compact ponds, medium irregular ponds, and small networked "bead-like" ponds. The purpose was to examine whether cooling performance depends only on water-body size or whether shape and compactness also influence cooling depth and stability.

Three distinct typologies of urban ponds were selected (Figure 8.) for detailed analysis based on their size, shape, and compactness. This selection was designed to test the relationship between shape resilience and the ability of water bodies to maintain a stable Urban Cool Island (UCI) core. The first typology, represented by the RU Pond, characterizes a large and relatively compact water body that functions as a major internal cooling sink within the city. The second typology, represented by the Shiroil-Baliapukur Pond, captures a medium-scale water body with low compactness and an irregular perimeter, allowing assessment of how irregular geometry may increase vulnerability to surrounding urban heat. The third typology consists of a networked "bead-like" system of 31 small, highly compact ponds interconnected by a green belt stretching from Greater Road to Jhautola. This category was selected to evaluate the cumulative microclimatic stability provided by fragmented but spatially distributed blue-green infrastructure in dense urban fabrics. The morphological metrics for these representative categories are presented in Table 2.

Table 2. Morphological Metrics of Selected Blue Infrastructure Typologies in Rajshahi.

Typology	Representative Site	Count (n)	Area (m^2)	Perimeter (m)	Compactness
Large-Compact	RU Pond	1	81,845	1,223	0.687
Medium-Irregular	Shiroil-Baliapukur Pond	1	25,117	1,107	0.258
Small-Networked	Interconnected "Beads (Greater Road to Jhautola)"	31	3708.9±3133.3[1]	236.5±108.8[1]	0.771±0.13[1]

[1] Values for the small-networked typology represent the Mean ± Standard Deviation across 31 features. Median values for this group are 2,528.6 m2 (Area), 197.67 m (Perimeter), and 0.791 (Compactness).

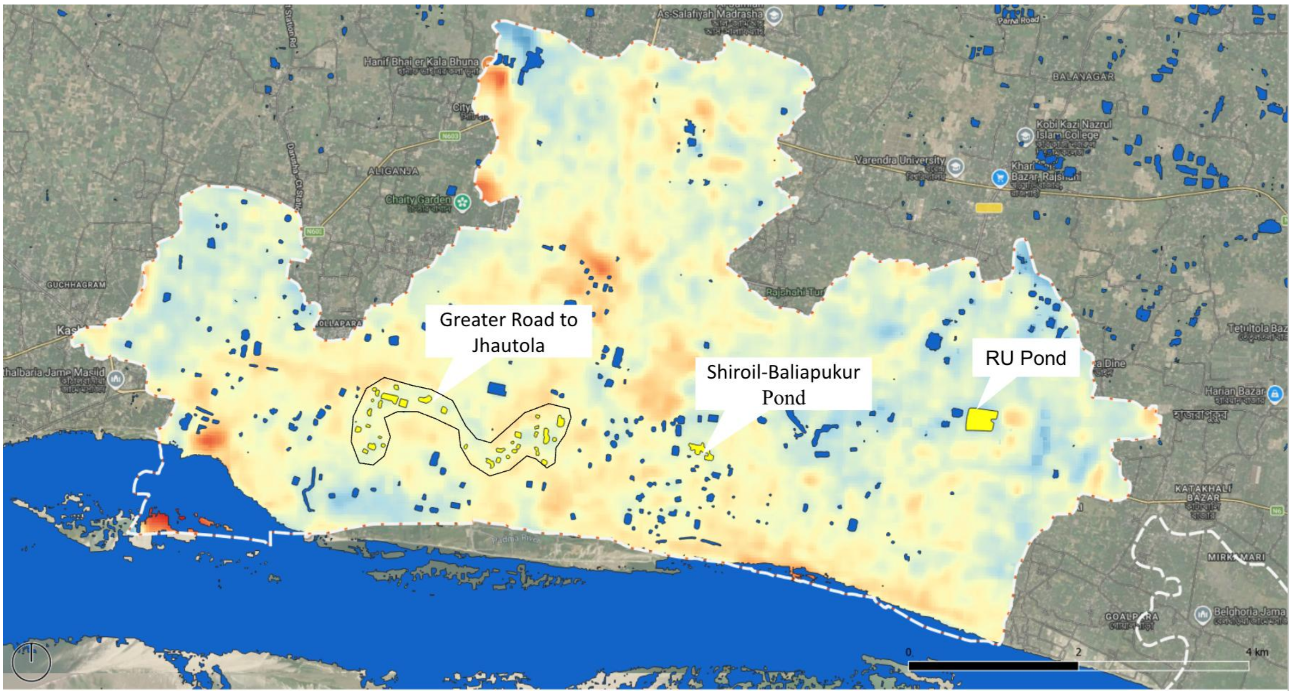

Figure 8. Location of selected urban pond typologies within Rajshahi City Corporation, showing in yellow the RU Pond, Shiroil-Baliapukur Pond, and the networked "bead-like (Greater Road to Jhautola)" pond system used for morphological and UCI cooling analysis.

2.5 Microclimatic Gradient Profiling

The cooling influence of blue infrastructure was finally evaluated through cross-sectional profiling using the QGIS Profile Tool. Transverse and longitudinal profiles were drawn across the Padma River and selected urban ponds to model the spatial cooling gradient from water surfaces toward surrounding urban land covers. This approach allowed the study to examine not only the cooling intensity of each blue-infrastructure feature, but also the distance over which the cooling effect remained effective before the surrounding land surface temperature returned to the urban average.

To quantify the cooling gradient, three parameters were used: cooling potential (ΔT), cooling reach (ΔX), and cooling gradient (CG). Cooling potential refers to the degree to which a water body lowers surface temperature relative to the mean urban LST of Rajshahi City Corporation, which was calculated as 37.41°C. Cooling reach represents the distance from the cooling core to the point where LST recovers to, or exceeds, the urban mean. The cooling gradient was then calculated by dividing cooling potential by cooling reach. This value indicates how quickly the cooling effect weakens with distance from the water body.

$$\Delta T = LST_{urban\ mean} - LST_{min}$$

Equation 3. Cooling potential of blue infrastructure, where $LST_{urban\ mean}$ is the mean LST of the urban core and LST_{min} is the minimum LST recorded along the profile line.

$$\Delta X = D_{LST \geq LST_{urban\ mean}} - D_{LST_{min}}$$

Equation 4. Cooling reach of blue infrastructure, where ΔX represents the distance from the minimum-temperature cooling core to the point where LST returns to or exceeds the urban mean.

$$CG = \frac{\Delta T}{\Delta X}$$

Equation 5. Cooling gradient of blue infrastructure, where CG represents the rate of temperature recovery per unit distance from the cooling core.

Or, CG may also be reported as °C/100 m:

$$CG_{100m} = \frac{\Delta T}{\Delta X} \times 100$$

Equation 6. Standardized cooling gradient expressed as °C per 100 m, used to compare the rate of temperature recovery across river and pond profiles.

2.5.1 River Microclimatic Gradient Profiling

For the Padma River, four transverse profile sections were selected along the southern edge of Rajshahi City Corporation to evaluate riverine cooling penetration across different urban morphologies. The rationale for selecting four profiles was to capture variation in the land-water interface, including sandy chars, compact residential areas, commercial and industrial zones, institutional areas, vegetated buffers, and open or sparsely built land covers. Since the Padma River represents the largest blue-infrastructure feature in the study area, these profiles were designed to examine how far river-induced cooling travels inland and how different land-cover transitions either support or weaken that cooling effect.

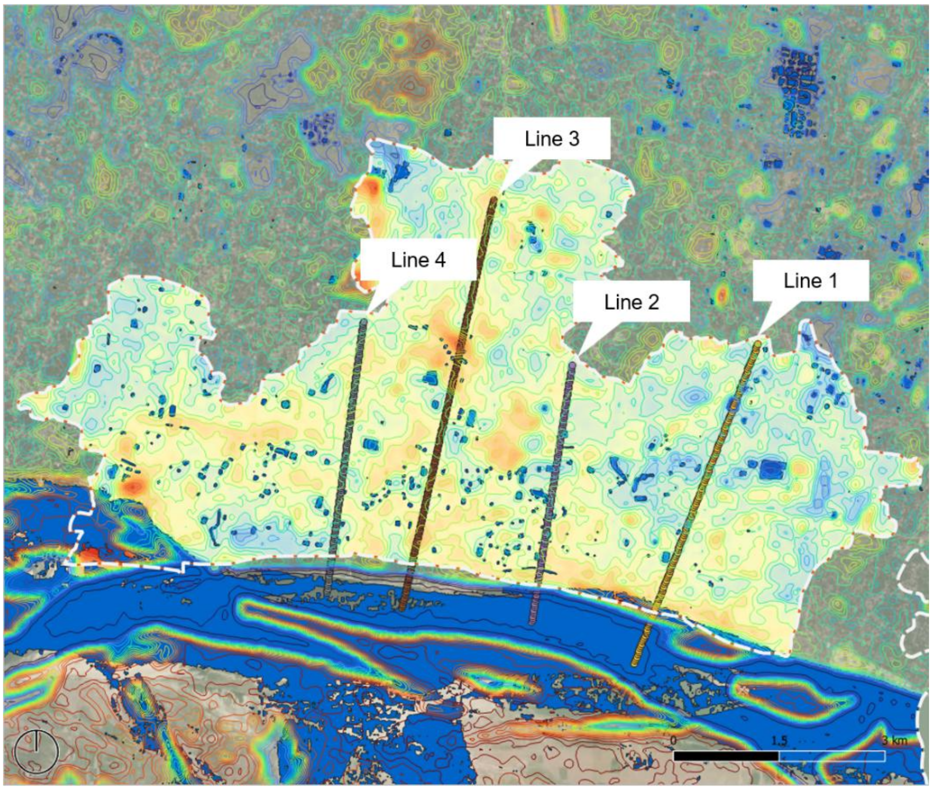

Figure 9. Location of four transverse profile sections used to evaluate the cooling penetration of the Padma River across different land-cover and urban morphology conditions in Rajshahi City Corporation.

The first profile was drawn from the Padma River across a sand-covered char, Kazla Residential Area, Rajshahi University, and Meherchandi Residential Area. This section was selected to examine how the cooling effect changes when riverine cooling first encounters exposed sandy surfaces and then transitions into compact residential and institutional/open mid-rise areas. The second profile extends from the Padma River toward Hadir Moor–Baliapukur, the Sericulture Institute, and Padma Residential Area. This line represents a compact urban edge where river cooling is expected to be rapidly weakened by dense residential development. The third profile passes through Shaheb Bazar Commercial Area, Uposhohor Residential Area, Sapura Industrial Area, and a sparsely built institutional zone. This section was selected because it crosses some of the most heat-intensive commercial and industrial morphologies of the city. The fourth profile extends from the Padma River through a char, Central Jail area, Sepaipara Residential Area, Rajshahi Medical College, and Terokhadia Residential Area. This section captures a more open and institutional corridor where riverine cooling may penetrate further inland.

Table 3. Summary of Padma River profile sections, showing location, land-cover sequence, and analytical rationale for microclimatic gradient profiling.

Profile	Primary Land Use Sequence	Min Temp (River)	Max Temp (Urban)	Thermal Characteristic	Rationale for selection
Line 1	River → Char → Compact Low → Open Mid	28.86ºC	42.89ºC	Rapid heating due to sand; RU stabilizes temp.	Tests the effect of sandy char and institutional open space on river cooling penetration
Line 2	River → Compact Low → Scattered Tree	28.72ºC	40.41ºC	Quickest "Flattening" due to edge density.	Represents compact river-edge development where cooling may be rapidly lost
Line 3	River → Comm. → Compact Mid → Industrial	28.57ºC	44.07ºC	Most extreme heat: Cooling lost in Shaheb Bazar.	Captures the commercial-industrial heat corridor and evaluates resistance to river cooling
Line 4	River → Char → Sparsely Built → Open Mid	28.65ºC	39.38ºC	Furthest cooling reach due to "Open" morphology.	Tests whether open and institutional morphologies allow deeper cooling penetration

The LST values extracted from each river profile were plotted against distance from the river. The point of minimum LST was treated as the cooling core, and the distance at which the profile reached the RCC mean LST was identified as the cooling reach. These profiles were also used to interpret the role of land-cover interfaces. Vegetated, open, or institutional areas were interpreted as potential thermal bridges because they may allow river cooling to extend inland. In contrast, sandy chars, compact built-up areas, commercial blocks, and industrial surfaces were interpreted as thermal barriers because they may accelerate temperature recovery and reduce the effective cooling distance.

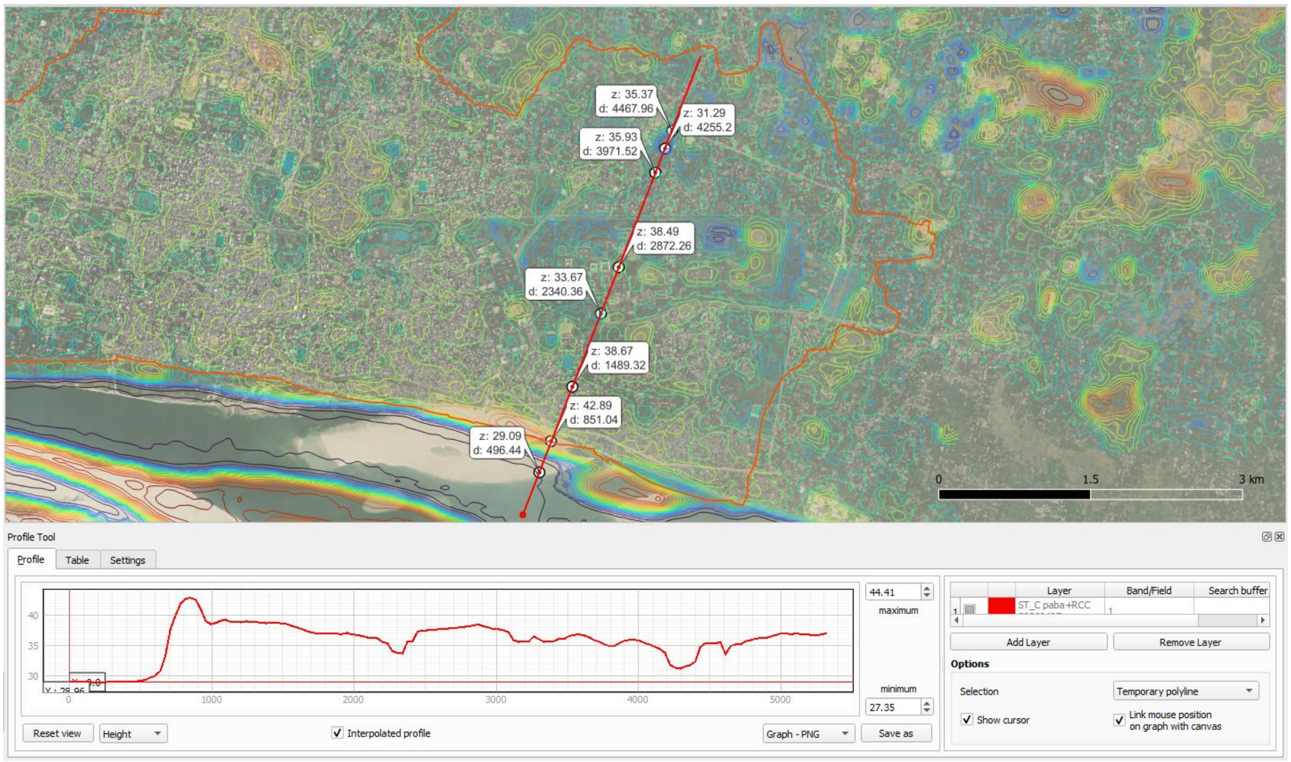

Figure 10. Representative micro-scale profiles (Line 1) illustrating the cooling potential (ΔT), cooling reach (ΔX) across Line 1 in Padma river in Rajshahi.

2.5.1 Pond Microclimatic Gradient Profiling

The pond typologies were selected to capture three contrasting morphological conditions of urban blue infrastructure (Table 4): size dominance, shape irregularity, and networked distribution. The RU Pond represents a large and relatively regular pond, with an area of 81,845 m² and compactness of 0.69, allowing assessment of the cooling role of a major internal water body. The Shiroil-Baliapukur Pond represents a medium-sized but highly irregular pond, with an area of 25,118 m² and compactness of 0.26, enabling examination of how low compactness and irregular perimeter conditions may reduce cooling stability. The Greater Road to Jhautola pond system represents a network of 31 small bead-like ponds connected by green corridors, with an average area of 3,709 m² and compactness of 0.77, allowing assessment of whether multiple small but compact water bodies can collectively support distributed cooling. These three typologies therefore provide a comparative basis for evaluating whether UCI performance is governed primarily by size, by shape regularity, or by spatial connectivity.

Table 4. Morphological and thermal characteristics of selected pond typologies representing large-regular, medium-irregular, and small-networked blue infrastructure in Rajshahi.

Typology	**Example Site**	**Area (sqm)**	**Compactness (C)**	**Mean Min LST**	**Cooling Potential (ΔT)**	**Cooling Reach (ΔX)**
Type i: Large/Regular	RU Pond	81,845	0.69	30.50ºC	6.98ºC	582.81m
Type ii: Med./Irregular	Shiroil-Baliapukur	25,118	0.26	35.27ºC	2.15ºC	237.73m
Type iii: Beads/Network	Greater Road to Jhautola	3709	0.77	35.40ºC	2.19ºC	234.08m

A similar profiling approach was applied to selected urban ponds; however, unlike the river profiles, pond analysis used both transverse and longitudinal sections (Figure 11). This was necessary because ponds are smaller, more geometrically varied, and spatially embedded within dense urban fabric. Transverse profiles were used to examine edge-to-edge cooling depth and temperature recovery from the pond center toward adjacent built-up or vegetated areas. Longitudinal profiles

were used to examine the continuity of cooling, particularly in the case of the networked "bead-like" pond system connected by green belts.
Seven pond profile sections (Table 5) were used in total across the three selected pond typologies: the large-compact RU Pond, the medium-irregular Shiroil-Baliapukur Pond, and the small-networked pond system. The RU Pond profiles were used to examine the cooling behavior of a large and relatively compact water body. The Shiroil-Baliapukur Pond profiles were used to evaluate whether an irregular perimeter weakens cooling stability despite moderate water-body size. The networked pond profiles were selected to assess whether multiple small but compact ponds produce cumulative cooling stability across a longer urban corridor.

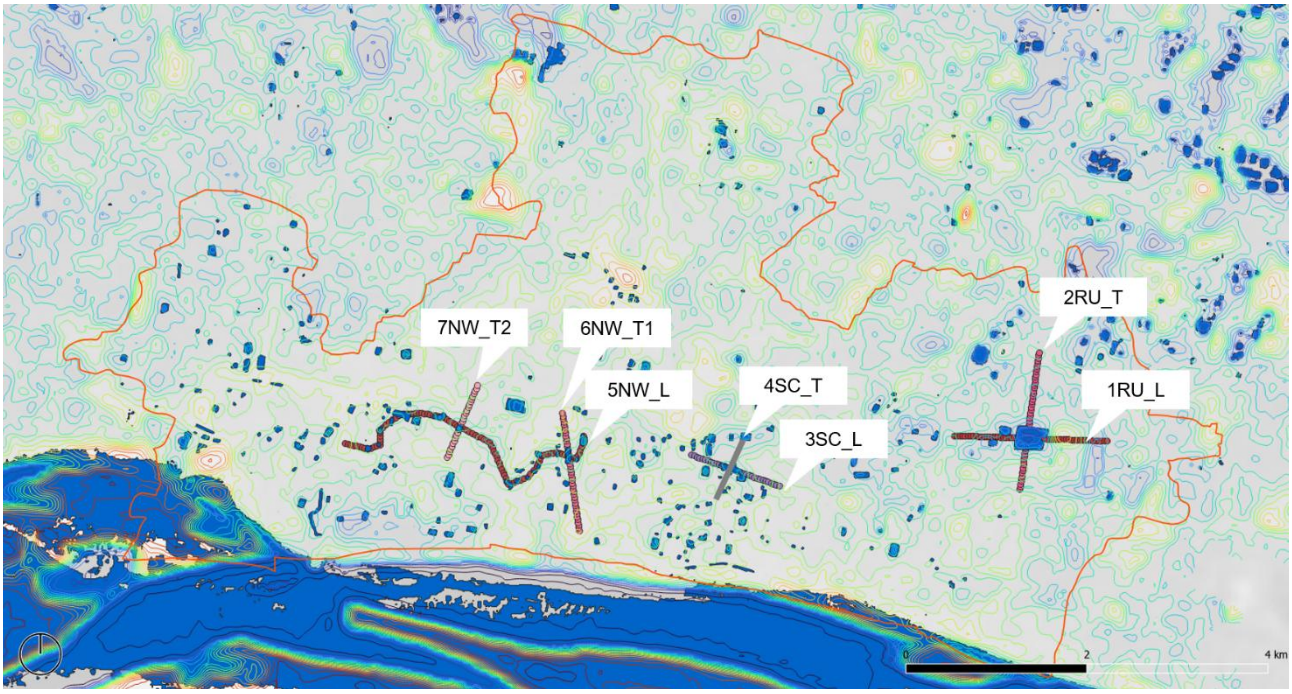

Figure 11. Location of pond profile sections used to evaluate cooling gradients across selected pond typologies, including the RU Pond, Shiroil-Baliapukur Pond, and networked "bead-like (Greater Road to Jhautola)" pond system.

Table 5. Summary of Ponds' profile sections, showing location, land-cover type, temperature, cooling potential and reach for microclimatic gradient profiling.

Profile	Location	Typology	Primary Land Use	Min. Temp. in ⁰C	Max. temp. in ⁰C	Cooling Potential (ΔT) in ⁰C	Cooling Reach (ΔX) in m
1RU_L	Rajshahi University	Large/ Regular/ longitudinal	B. Scattered Tree (Educational Institute)	30.47	40.73	≈6.84	≈496.00
2RU_T	Rajshahi University	Large/ Regular/ transverse	B. Scattered Tree (Educational Institute)	30.52	38.86	≈7.12	≈669.62
3SC_L	Shiroil-Baliapukur	Medium/ Irregular/ longitudinal	3. Compact low-rise (Residential) and B. Scattered Tree	35.26	38.41	≈2.34	≈318.41
4SC_T	Shiroil-Baliapukur	Medium/ Irregular/ transverse	3. Compact low-rise (Residential) and B. Scattered Tree	35.28	37.85	≈1.95	≈157.05
5NW_L	Greater Road to Jhautola	Bead/ Network/ longitudinal	2. Compact midrise (Residential)	35.29	39.59	≈2.06	≈368.90
6NW_T1	Greater Road to Jhautola	Bead/ Network/ transverse	2. Compact midrise (Residential)	35.70	41.11	≈1.91	≈188.02
7NW_T1	Greater Road to Jhautola	Bead/ Network/ transverse	2. Compact midrise (Residential)	35.19	39.80	≈2.60	≈145.31

Overall, the microclimatic gradient profiling method provided a spatially explicit means of evaluating how blue infrastructure cools the city, how far the cooling effect travels, and how quickly it is interrupted by surrounding land-cover conditions. By integrating ΔT\Delta TΔT, ΔX\Delta XΔX, and CGCGCG, the analysis moves beyond identifying cool surfaces and instead quantifies the performance of each blue-infrastructure typology as an active component of Rajshahi's urban thermal regulation system.

3. Results

3.1 Urban–Rural Thermal Baseline: RCC and Paba

The first step in analyzing thermal divergence was to establish a baseline comparison between the compact urban core of Rajshahi City Corporation (RCC) and the surrounding rural periphery of Paba Upazila. Zonal statistics applied to the Landsat 9 dataset indicate that while the mathematical means are remarkably close—separated by an average regional index of just 0.41°C—the true thermal structure is explained by their median values and variance profiles (Figure 12). RCC exhibits a narrow, highly homogeneous thermal footprint with a standard deviation of 1.86°C, confirming the existence of a continuous, stagnant "urban heat plateau."

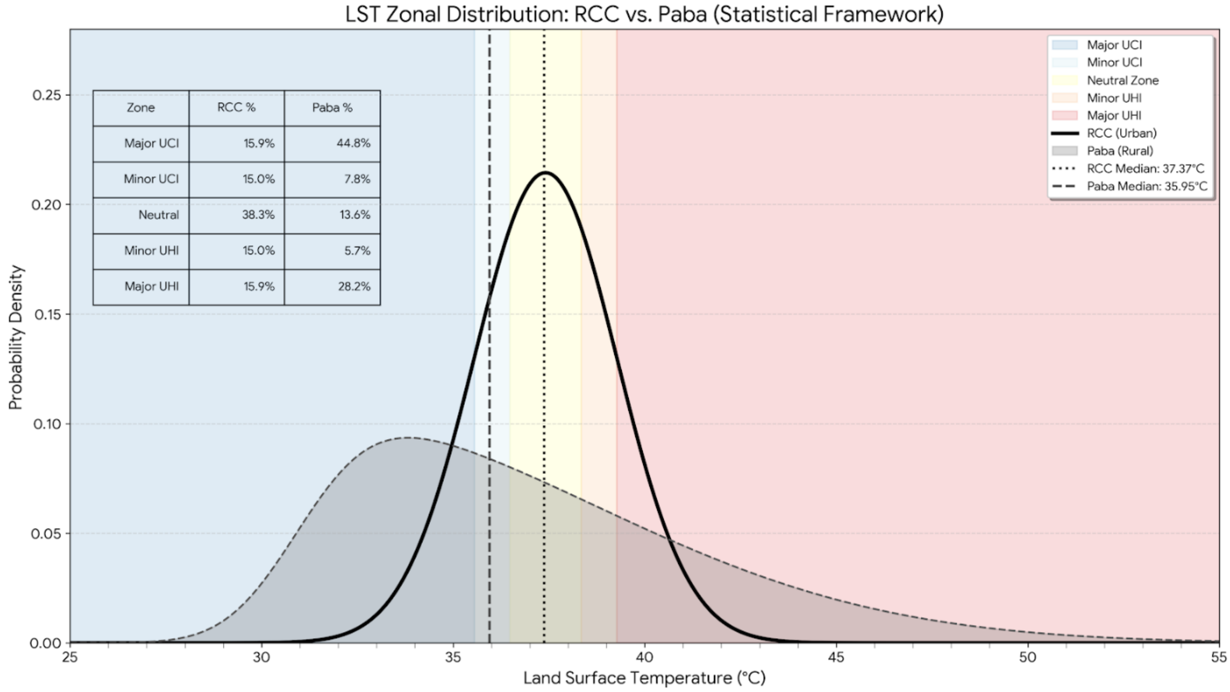

Figure 12. Comparative distribution of Land Surface Temperature between Rajshahi City Corporation (RCC) and Paba Upazila, illustrating urban thermal uniformity and rural/peri-urban thermal variability.

In contrast, Paba Upazila exhibits wide thermal volatility with a standard deviation of 4.80°C, reflecting a highly diverse, fragmented rural landscape that ranges from dense vegetative cooling paths to severe exposed soil hotspots. This structural variance proves that while the open rural landscape is capable of achieving deep baseline cooling during the day, it is simultaneously prone to localized radiative extremes. The full statistical distribution of the macro-scale thermal baseline is structured in Table 6.

Table 6. Comparative LST baseline statistics for the urban core (RCC) and rural baseline (Paba).

Spatial Analysis Unit	Area (km^2)	Mean LST (°C)	Median LST (°C)	Std. Deviation (°C)	Minimum LST (°C)	Maximum LST (°C)
Paba Upazila (Rural Baseline)	304.17	37.00	35.95	4.80	23.36	52.27
Rajshahi City Corporation (Urban Core)	47.06	37.41	37.37	1.86	28.84	47.37
Divergence Index (Δ)	-	+0.41	+1.42	-	+5.48	-4.90

3.2 Spatial Structure of Delineated Thermal Nodes

The pixel-level application of the standard-deviation-based classification framework confirms that Rajshahi's thermal landscape is highly fragmented rather than uniform. The Neutral Zone ($\mu \pm 0.5\sigma$) covers less than a quarter of the urban core, proving that the city is divided into opposing extremes of localized heat stress and microclimatic relief. Major Urban Heat Island (UHI) nodes ($> 39.27°C$) occupy 26.3% of the municipal area, primarily corresponding to industrial metallic roofing clusters, high-density residential fabrics, and unshaded soils.

Conversely, Major Urban Cool Island (UCI) nodes ($< 35.54°C$) cover 29.6% of the city, dominated by the active surface of the Padma River corridor and reinforced inland by high-biomass institutional sanctuaries. The spatial distribution and total area occupancy of these five statistically defined zones are presented in Table

Table 7. Zonal distribution and spatial extent of delineated thermal nodes within RCC.

Thermal Zone Delineation	Temperature Threshold Criteria (°C)	Total Calculated Area (km^2)	Percentage of Urban Core (%)	Microclimatic Significance
Major Urban Cool Island (UCI)	< 35.54	13.93	29.6	Core macro-sinks and river channel
Minor Urban Cool Island (UCI)	35.54 to 36.48	11.39	24.2	Vegetated buffers and large ponds
Neutral Thermal Background	36.48 to 38.34	11.29	24.0	Median baseline urban matrix
Minor Urban Heat Island (UHI)	38.34 to 39.27	11.34	24.1	Medium-density built-up residential
Major Urban Heat Island (UHI)	39.27	12.38	26.3	Exposed sandbars, industrial clusters

3.3 Cooling Efficacy of the Padma River

The cooling effect of the Padma River was evaluated through four profile lines drawn along the river's southern edge. The profiles showed that the river provided cooling up to 1.7 km in open areas. However, its cooling efficacy diminished when it encountered compact built-up zones or exposed sandy river shores.

Table 8. Cooling characteristics of Padma River profile sections across different land-cover sequences.

Profile	Cooling Potential (ΔT)	Cooling Reach (ΔX)	Cooling Gradient (CG)
Line 1	8.55°C	≈780 m	1.1 °C/100m
Line 2	8.69°C	≈670 m	1.3 °C/100m
Line 3	8.84°C	≈850 m	1.0 °C/100m
Line 4	8.76°C	≈1,705 m	0.5 °C/100m

The microclimatic cross-sections extracted using the QGIS Profile Tool map the spatial decay of riverine cooling as it encounters different municipal configurations (see Figure 13). At the starting coordinate (0 meters), all four transects originate within the core channel of the Padma River, recording the lowest surface temperature floor in the region (28.84°C). However, the rate of temperature recovery back toward the urban mean baseline (37.41°C) varies strictly according to the surface conditions of each line. Along Line 1 (East sector) and Line 4 (West sector), where extensive unshaded sandbars (chars) separate the core water surface from the built environment, the profiles show an immediate thermal escalation. LST spikes by more than 6.0°C within the first 500 meters of the bank, crossing the regional urban mean long before entering the residential blocks. Along the central urban transect (Line 3), which moves directly from the open water into the high-density built environment of Shaheb Bazar, the profile experiences a sudden rise, recovering fully to the urban mean within a narrow horizontal distance of 670 to 850 meters. Conversely, the Line 1 profile exhibits prolonged low temperatures as it enters the Rajshahi University campus, where the cooling effect exhibits its maximum horizontal reach, traveling up to 1.7 kilometers inland before returning to the background urban mean.

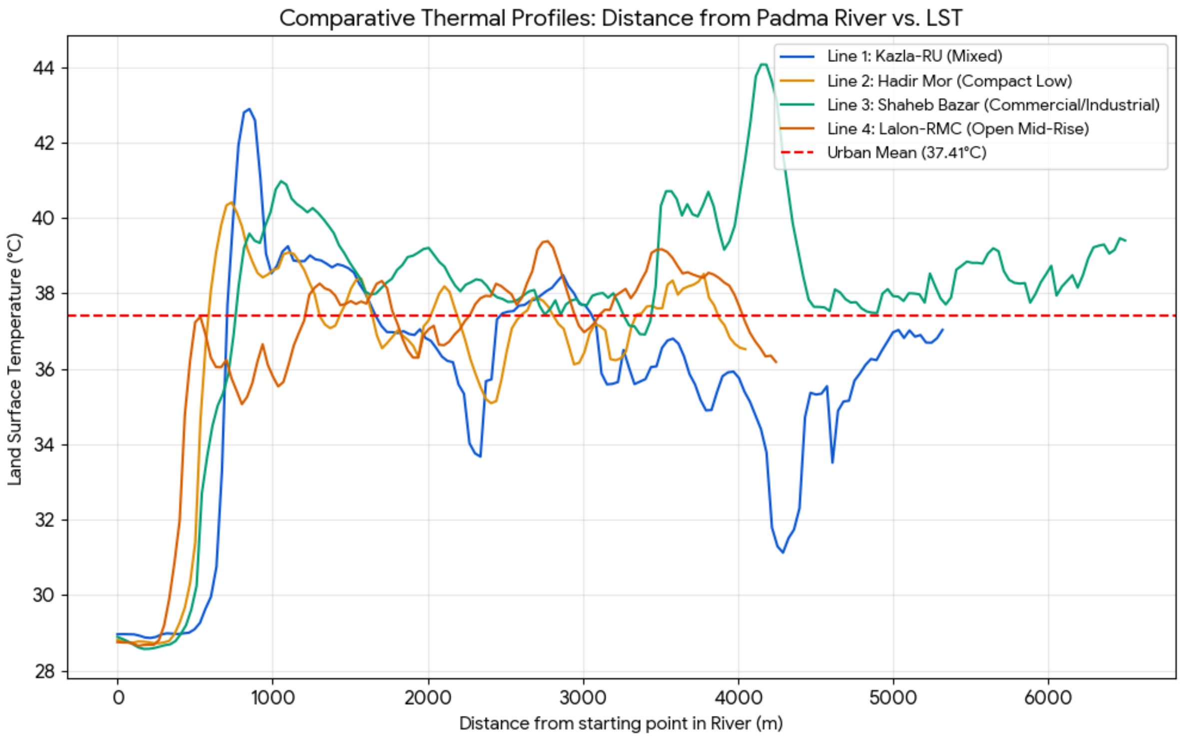

Figure 13. Cross-sectional thermal profile extraction (Lines 1–4) mapping Land Surface Temperature (°C) against horizontal inland distance (meters) from the Padma River core channel.

3.4 Cooling Efficacy of Urban Pond Typologies

The three selected pond typologies—RU Pond (large/regular), Shiroil-Baliapukur (medium/irregular), and Greater Road to Jhautola networked pond system (small/compact)—showed differing cooling potential. The RU Pond exhibited the highest cooling potential (ΔT = 6.98°C) and a cooling reach of 582.81 m.

Table 9. Cooling performance of selected pond typologies in Rajshahi.

Typology	Example Site	Cooling Potential (ΔT)	Cooling Reach (ΔX)	Cooling Gradient (CG)
Type i: Large/Regular	RU Pond	6.98ºC	582.81m	1.20 ºC/100m
Type ii: Med./Irregular	Shiroil-Baliapukur	2.15ºC	237.73m	0.90 ºC/100m
Type iii: Beads/Network	Greater Road to Jhautola	2.19ºC	234.08m	0.94 ºC/100m

The integrated analysis of North-South (Transverse) and East-West (Longitudinal) profiles across the selected water body typologies reveals that cooling distribution is fundamentally governed by directional geometry. For the highly compact RU Pond (C=0.687), the thermal gradients along both axes are nearly identical, demonstrating isotropic cooling behavior where a maximum temperature drop of 10.25^0C is projected uniformly into the surrounding matrix.

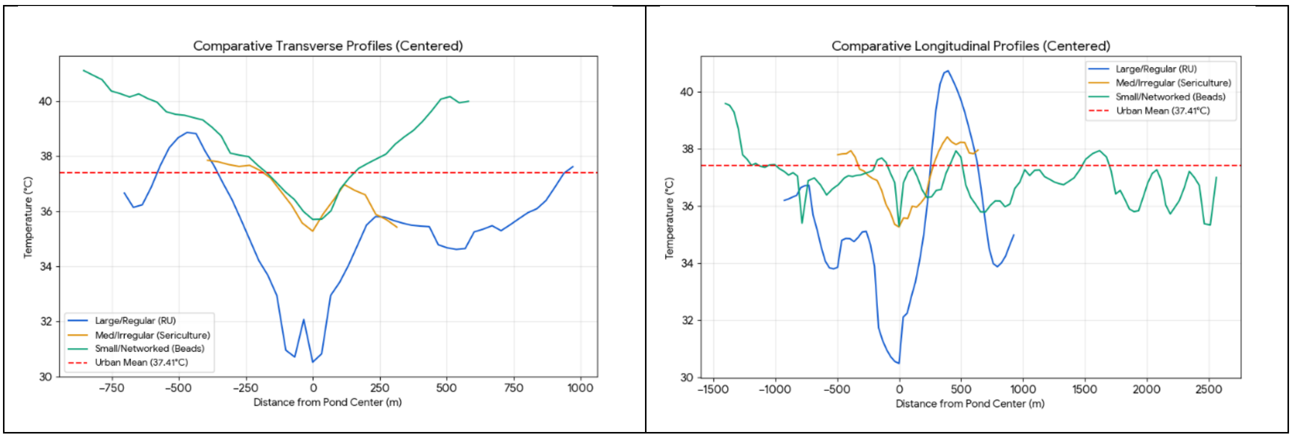

Figure 14. Direct comparison of directional cooling gradients across the three selected water body test cases: (a) Transverse cross-sections (North–South axis), and (b) Longitudinal cross-sections (East–West axis).

4. Discussion

4.1 The "Thermal Leap" and "Thermal Barriers" along the Padma Riverfront

The cross-sectional profile assessments generated perpendicular to the Padma River reveal an abrupt microclimatic shift at the city's edge, termed the "Thermal Leap." While the core water channel establishes a regional macro-scale cool sink (~28.8°C), this thermal relief fails to propagate uniformly inland. Cross-sectional microclimatic tracking demonstrates that surface temperature spikes by over 6.0°C within the first 500 meters of the riverbank along specific transects. This immediate loss of relief is directly governed by the land-cover typologies at the water-land interface, which can act as either "Thermal Barriers" or "Thermal Bridges."

In the western and eastern extremities (Line 1 and Line 4), the river is bordered by "chars"—extensive, unshaded sandbars. Due to the fine sand composition, these dry surfaces absorb high levels of solar radiation and lack moisture content, causing their surface temperatures to soar above 38.0°C. These chars function as morphological "heat walls," choking the cool riverine airflow and creating a severe local microclimatic barrier before the relief can reach residential blocks. Conversely, where the river directly abuts institutional areas and sparsely built spaces, the cooling effect propagates deeper, highlighting that the physical edge configuration dictates the regional performance of macro-sinks.

4.2 Shape Resilience vs. Thermal Overwhelming in Urban Pinks

At the micro-scale, the comparative profiling of internal urban water bodies confirms that shape geometry functions as the gatekeeper of a pond's microclimatic stability. Elongated and irregular polygons increase the perimeter-to-area ratio, expanding the zone of contact between cooler water volumes and heat-radiating impervious gray surfaces. As observed in the Shiroil-Baliapukur Pond, this edge exposure leads to thermal overwhelming, where the high radiative load from surrounding asphalt and compact low-rise built forms effectively neutralizes the evaporative cooling process.

Conversely, compact features demonstrate high "shape resilience." The circular geometry of the RU Pond minimizes this boundary contact, preserving a dense internal cool core that remains insulated from the surrounding urban heat plateau. This finding reframes the planning approach to blue infrastructure, moving beyond absolute area requirements to prioritize shape optimization.

Furthermore, the statistical performance of the 31 networked ponds demonstrates that small, fragmented water features can achieve significant microclimatic efficacy if they are spatially organized into clusters. Although individual ponds lack the volume to generate wide cooling zones, their high average compactness (0.771) keeps them thermally viable. When linked by a contiguous green belt, they act as repeated thermal obstacles that interrupt continuous heat accumulation, preventing the formation of contiguous heat islands in dense residential sectors.

4.3. Synergy and Planning Implications for Resilient Urban Morphology

Integrating these findings provides a structural framework for climate-responsive urban design in secondary tropical cities. By applying the Local Climate Zone (LCZ) classifications to the land-water interface, it becomes evident that the cooling performance of both rivers and ponds is co-dependent on the surrounding building height, density, and biomass layout. Open mid-rise and institutional morphologies function as active "Thermal Bridges" due to their low building coverage and high pervious surface fraction, which allow natural cooling gradients to extend up to 1.7 km inland—nearly three times further than compact, high-density blocks.

This establishes a clear planning guideline: to maximize the microclimatic utility of macro-sinks like the Padma River, municipal layout regulations must protect clear "Green Ventilation Corridors" running perpendicular to the riverbank. Protecting internal compact pond networks from unauthorized infill is critical; they serve as the city's internal climate regulators, stabilizing the urban thermal field where macro-riverine cooling cannot reach.

5. Conclusions

This study evaluated the microclimatic performance of blue infrastructure in Rajshahi, Bangladesh, by linking satellite-derived surface temperature anomalies with spatial morphology and cross-sectional profiling. The findings confirm that while Rajshahi is characterized by a homogeneous urban heat plateau (RCC Mean LST: 37.41°C, SD: 1.86°C), its blue infrastructure provides essential localized relief, establishing a total urban thermal range of 18.54°C. The Padma River operates as the primary macro-sink, but its inland reach is heavily restricted by dry, sand-covered chars that function as intense daytime "Thermal Barriers," causing surface temperatures to jump by over 6.0°C within 500 meters of the bank. At the neighborhood scale, morphology dictates cooling performance: highly compact standalone ponds ($C=0.687$) demonstrate strong shape resilience, preserving a stable cool core that yields a 10.25°C temperature drop, whereas irregular shapes are prone to thermal overwhelming. Small, fragmented pond clusters maintain high individual compactness and effectively stabilize the urban thermal field when linked by green corridors.

To translate these empirical findings into actionable urban policy, municipal planners in Rajshahi must transition from descriptive zoning to performance-based morphological design guidelines. First, the river-land interface must be prioritized for re-greening interventions; transforming unshaded, barren shores into structured green buffer corridors is essential to convert current thermal barriers into functional thermal bridges that channel river breezes inland. Second, urban building regulations along designated riverfront ventilation paths must strictly regulate building height-to-width ratios and density to prevent the formation of "morphological walls" that trap heat at the banks. Third, municipal authorities must enforce strict conservation protections for standalone traditional dighis and compact pond networks, treating them as structural thermal refuges rather than disposable land patches, while requiring an optimal Compactness Index ($C \geq 0.70$) for all new artificial urban blue features to maximize their microclimatic resilience.

While this research provides a high-resolution, standardized framework for evaluating blue infrastructure geometry, certain limitations remain that outline critical avenues for future inquiry. The utilize of Landsat 9 LST maps restricts the analysis to a single daytime snapshot (approximately 10:30 AM) during peak summer conditions, leaving the temporal variance and diurnal lag of these water bodies unexplored. Furthermore, the land cover classification was restricted to the polygonization of permanent water bodies, omitting a full multi-class 3D morphological assessment of building heights and sky-view factors. Future research should expand this model into a multi-temporal framework, utilizing day-and-night thermal composites to analyze how seasonal humidity variations alter evaporative cooling efficiency. Additionally, future investigations should employ advanced machine learning algorithms, such as Random Forest or gradient-boosting models, to statistically weigh the predictive importance of compactness, building volume, and biomass density across secondary tropical cities of the Global South.

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Conflicts of Interest
The authors declare that they have no financial, institutional, or personal conflicts of interest that could have inappropriately influenced or biased the objectivity of the work presented in this manuscript.

Data Availability Statement
The satellite rasters, vector boundaries, and extracted morphological shape files utilized in this study are derived from publicly accessible repositories, including the USGS EarthExplorer portal (Landsat 9) and the ESA WorldCover data platform. The processed tabular statistical data sheets generated during QGIS analysis are available upon reasonable request from the corresponding author.

Institutional Review Board Statement
This study was purely observational, utilizing publicly available satellite remote sensing products and administrative spatial boundaries. It did not involve any human subjects, animal testing, or sensitive field trials, and therefore did not require institutional review board approval or ethical clearance.

Credit Author Statement:
Md. Sabbir Ahsan: Conceptualization, Methodology, Software, Formal Analysis, Writing - Original Draft, Project Administration. **Sheikh Hameem:** Data Curation, Validation, Investigation, Writing - Review & Editing. **Md. Ezajul Islam:** Resources, Validation, Writing - Review & Editing.

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