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Research paper

doi: 10.30822/arteks.v11i2.4830

The UHI phenomenon and the potential for buffer zone development in Kayutangan heritage corridor

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ARTICLE INFO

Article history:
Received October 01, 2025
Received in revised form Nov. 05, 2025
Accepted March 12, 2026
Available online June 01, 2026

Keywords:
Environmental buffer zone
Kayutangan heritage area
Land surface temperature
Urban climate mitigation
Urban heat island

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ABSTRACT

The rising temperature of the Kayutangan Heritage Corridor (KHC) poses a risk to the sustainability of its historical value and the comfort of its microclimate. The UHI phenomenon in KHC development is vulnerable to the decline of historical value and microclimate quality. This study aims to assess the potential of the Brantas River Watershed as a buffer zone for KHC development. The method used is a three-stage analysis: first, land surface temperature (SST) data analysis to identify the distribution of hot and cold spots; second, direct surface temperature measurements to validate the LST; and third, Computational Fluid Dynamics (CFD) simulation of the existing thermal conditions of the KHC and its buffer zone. The LST distribution pattern forms the basis for formulating a UHI mitigation model. The CFD simulation results indicate that the Brantas River Watershed, which borders the KHC, has the potential to serve as a buffer zone for Kayutangan development. This mitigation strategy enables Kayutangan development to transform into a more resilient area through integration with its buffer zone.

Introduction

The success of the *Kayutangan* Heritage Area Revitalisation programme has had a positive impact, namely increased economic activity and developed the tourism sector. On the pain side, increased activity and development intensity will further increase the ecological burden on the *Kayutangan*n Heritage Corridor (KHC) and its surroundings. This condition is reflected in the increase in land surface temperature (LST), which, on a macro scale, is visible in the area's heat map. This research is crucial for anticipating the future, particularly the rapidly expanding development of the KHC. Massive spatial interventions can harm the surrounding environment; therefore, regional development must be integrated and prioritized to promote ecological sustainability. The development of the KHC has to be integrated with the development of its buffer zone. The buffer zone must be an integral part of the KHC development design to anticipate the UHI phenomenon.

The UHI phenomenon directly results from increased activity and intensive development, making the region progressively more vulnerable to changes in its microclimate (Buyadi, Mohd, and Misni 2013). Heritage areas, characterized by historical, cultural, and architectural significance, currently face substantial obstacles in adapting and effectively responding to urban development dynamics that prioritize modernization and contemporary architectural practices over the importance of maintaining historical integrity and ecological sustainability. On the one hand, heritage sites can serve as regional icons that shape a city's unique identity and character (Rostami, Khoshnava, and Lamit 2014). On the other hand, heritage areas are vulnerable to material degradation and increased risk of heat exposure due to rising ambient temperatures. This complex phenomenon creates a paradox: heritage areas, while crucial in representing the city's icons and character, simultaneously face microclimate challenges that significantly undermine their existence (Sayad et al. 2024).

This phenomenon occurs because artificial surfaces, such as asphalt and concrete, absorb and retain more heat than natural surfaces, like soil and vegetation. As a result, temperatures in urban areas are consistently higher during both the day and night than in surrounding rural areas. UHI has various negative impacts, including increased energy consumption for cooling, decreased air quality, and an increased risk of health problems such as heatstroke and respiratory illnesses (Filho et al. 2018; Islam et al. 2022). Areas particularly vulnerable to the impacts of UHI include the Central Business District (CBD) and new development areas such as the *Kayutangan* Heritage Area in Malang. The effect of UHI also has the potential to compromise temperature stability in urban buffer zones, as observed around the *Kayutangan* heritage area (Yadav and Singh 2024).

The UHI effect poses significant challenges and threatens the long-term sustainability and physical viability of heritage areas (Yadav and Singh 2024). This gap underpins research that investigates and explores effective and innovative strategies for developing urban environments into buffer zones. Solutions must harmonize heritage areas' "ecological relationship" with their surrounding natural environment (Rota, Gravante, and Zazzi 2019). This approach reconciles the need for heritage preservation with ensuring the resilience of heritage sites amidst the pressures of urban climate change. Malang's *Kayutangan* heritage area is a prime example of this phenomenon. The KHC, with its potential concentration of heritage buildings, currently faces adaptation challenges due to the degradation of old materials, the pressure of commercial activities, and rising urban temperatures (Respati Wikantiyoso and Santoso 2025).

The UHI phenomenon in the KHC indicates that this area experiences a significant temperature increase due to high building density, limited green open spaces, and the predominance of low-albedo pavement surfaces. Previous research indicates that daytime temperatures in the *Kayutangan* area can be 3-5°C higher than those in the surrounding suburban areas (Yetti, Soedharma, and Hariyadi 2011). Another factor that exacerbates this condition is the limited ability to modify building structures due to the lack of strict regulations governing the preservation of cultural heritage areas, which has implications for increasing surface heat.

In recent decades, relatively extensive studies have been conducted on UHI mitigation strategies, including implementing reflective surfaces, green roofs, and increased green space (Filho et al. 2018; Islam et al. 2022; Yadav and Singh 2024). However, in urban heritage areas, implementing these strategies often faces challenges due to aesthetics, conservation regulations, and space constraints. Therefore, UHI mitigation efforts are needed in the *Kayutangan* heritage area. Considering technical effectiveness, historical aspects, and environmental conservation approaches is essential. In recent decades, various studies have developed UHI mitigation strategies, including applying reflective surfaces, green roofs, and increased green open space (Jusuf et al. 2019). This research aims to bridge the need for urban development while providing a comfortable urban environment. Urban spatial sustainability is crucial in developing heritage areas in city centers, which face complex pressures of change. One form of sustainability is maintaining the heritage environment and harmonious urban development (Permana, Astuti, and Er 2017; R Wikantiyoso et al. 2021). The KHC's presence as a growth magnet and the *Brantas* watershed's potential to serve as a buffer zone should be integrated into a unified development plan. The resulting ideas and concepts are expected to contribute to establishing a resilient and sustainable *Kayutangan* heritage environment.

Therefore, mitigation strategies based on ecological and conservation approaches are crucial for maintaining the sustainability of the *Kayutangan* heritage area, a unique icon that has been developed as a heritage area capable of creating an economically vibrant and environmentally friendly urban environment.

The novelty of this research lies in its integrative approach, which connects the UHI phenomenon with the potential for developing landscape-based buffer zones in the context of cultural heritage areas. This study not only highlights the impact of rising temperatures (Haeri, Hassan, and Ghaffarianhoseini 2022; Islam et al. 2022; Buyadi, Mohd, and Misni 2013; Aini et al. 2025) on thermal comfort and the degradation of the historical value of the KHC but also offers a new perspective on microclimate mitigation by utilising the *Brantas* Watershed as an ecological and spatial element capable of reducing the effects of UHI. This approach expands the heritage conservation paradigm (Wong, Jusuf, and Tan 2011; Lafortezza and Sanesi 2019; Respati Wikantiyoso and Santoso 2025) beyond simply preserving the form and function of buildings to integrating natural environmental systems as an adaptive strategy for urban climate change.

Furthermore, the combined use of satellite imagery analysis to identify LST, field temperature measurements, and Computational Fluid Dynamics (CFD) simulations provides a significant methodological contribution to mapping and validating thermal phenomena in heritage areas. The combination of these three approaches provides a spatial-thermal analysis model that has not been widely applied in studies of tropical heritage areas. Thus, this study presents a new conceptual model of ecological zoning-based UHI mitigation that can serve as a reference for the development of sustainable heritage areas in tropical cities, such as Malang.

The success of this research can serve as a reference for planning resilient heritage areas to climate change and strengthening the relationship between heritage areas and their buffer zones. The results of this study are expected to serve as a basis for policymakers and urban planners to develop heritage area revitalization strategies that incorporate visual conservation and support comprehensive environmental sustainability.

Methods

This study examines the potential for developing a buffer zone on the *Brantas* watershed as a mitigation strategy to realize an ecological heritage area in *Kayutangan*. The analysis was conducted by mapping the area's geometry and thermal-atmospheric parameters and developing a buffer zone development scenario that functions as a thermal control element and adaptive public space. The distribution patterns and characteristics of the area's surface heat (hot-cold spots) were the basis for determining the UHI mitigation model. The analysis employed three methods:

1. Satellite heat map data analysis

First, the study focused on surface temperature mapping through satellite image processing (Parmeggiani et al. 2024). The satellite images used were Landsat 8/9 TIRS, with higher spatial resolution for local analysis. The selected images were first processed through atmospheric correction, followed by the determination of surface emissivity using an NDVI-based approach (Workie and Debella 2018), and a split-window algorithm to obtain accurate LST values. The extracted surface temperature data were then mapped spatiotemporally, showing the distribution of heat in the *Kayutangan* area, including differences in heat intensity between the core of the *Kayutangan* heritage corridor area and the buffer zone around the *Brantas* River Watershed. This analysis enabled the identification of hotspots and temperature change trends, which served as the basis for assessing the intensity of the UHI phenomenon in the study area.

2. Surface heat measurement data analysis

Second, field measurements were conducted to calibrate and validate the satellite analysis results, providing more detailed microclimate data for CFD simulations. Temperature and humidity measurements in this study were conducted by students who were part of the research team. The measurements were conducted by four teams, each consisting of two students and eight students who took measurements at 100 points. Each point was measured three times, in the morning (06:00-08:00), afternoon (13:00-14:00), and evening (16:00-17:00), resulting in a total of 300 measurements.

3. CFD simulation of the existing area and its intervention scenario

Third, the CFD-based simulation method dynamically analyzes thermal changes and wind patterns (Shi et al. 2015). This model enables the simulation of existing conditions and the assessment of the impact of mitigation interventions on temperature distribution and airflow. Data on temperature, humidity, wind speed, and surface material characteristics were collected through field measurements, satellite imagery, and digital mapping (Alvioli et al. 2018; AWASTHI et al. 2023; Bozonnet et al. 2015; Yesserie 2009). A CFD model was developed using a high-resolution mesh/grid, with parameters reflecting real-world conditions. Transient simulations were conducted to understand daily thermal fluctuations and the effectiveness of UHI mitigation strategies. CFD works by numerically solving the Navier-Stokes and energy equations in complex urban domains. Kozak et al. (2020) stated that CFD methods can accurately reproduce surface temperature distributions and airflow at the metropolitan scale, providing valuable insights into the impact of UHI mitigation interventions.

By integrating these three approaches, the study can provide a comprehensive picture of the thermal dynamics of the *Kayutangan* heritage corridor and its buffer zone. Satellite analysis provides a broad spatial context, field measurements enhance data accuracy, and CFD simulations enable projections of the impacts of buffer zone design interventions (Aini et al. 2025).

Results and discussion

Kayutangan Heritage Area, Malang

The Kayutangan Heritage Area in Malang City is a historical corridor in the city center, specifically around Jalan Kayutangan, Kauman Village, and Klojen District. This area can be mapped at coordinates of approximately -7.979872°S and 112.627353°E, placing it in the heart of Malang City with an average elevation of roughly 506 meters above sea level.

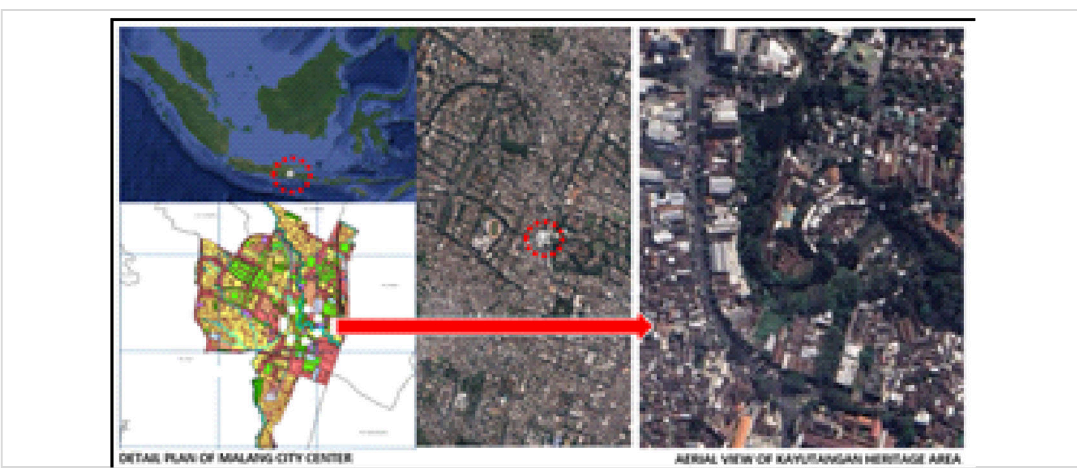

Figure 1. Geographical position of *Kayutangan* Heritage Area Malang

According to previous research, Malang's *Kayutangan* urban heritage area (figure 1) experiences significant temperature increases due to high building density, minimal green space, and the dominance of low-albedo pavement surfaces (Santamouris 2014). Previous research indicates that daytime temperatures in the *Kayutangan* area can be 3–5°C higher than those in surrounding suburban areas (Dezaki and Walczak 2022; Jennerjahn, Adi, and Schroeder 2013). Another factor exacerbating this situation is the limited ability to modify building structures due to lax regulations regarding the preservation of cultural heritage areas. Therefore, UHI mitigation in this area requires an approach that considers both technical effectiveness and the historical and conservation aspects of the natural buffer environment (figure 2).

Figure 2. *Kayutangan* Heritage Area

In this study, the *Kayutangan* Heritage Area is divided into two parts: the KHC area and the Buffer Zone area (figure 3). These two areas serve as units of analysis that must be integrated in the development of the *Kayutangan* Heritage Area. In reality, development has focused solely on the *Kayutangan* Heritage Corridor.

The KHC is a historical corridor experiencing pressures from urbanization, climate change, and the increasing Urban Heat Island (UHI) phenomenon. This situation presents a challenge due to the limitations in physical interventions on heritage buildings, which must maintain the authenticity of their structures and materials by regulation. On the other hand, green areas surrounding the *Brantas* Watershed can serve as an ecological buffer zone, reducing the impact of heat and maintaining a balanced microclimate (figure 3). The presence of river buffers and surrounding vegetation in the KHC plays a crucial role in enhancing the cooling effect, thus reinforcing the unique climatic characteristics of the KHC.

Figure 3. *Kayutangan* Heritage corridor and buffer zone area delination

The once-shaded streets and alleys of the heritage corridor are now increasingly filled with impermeable pavement, paved sidewalks, and heat-absorbing parking areas. The lack of shading vegetation also worsens thermal comfort, especially for pedestrians and residents in narrow alleys. Another impact of this rising temperature (Ismail, Samad, and Malek 2008; Jain 2023) is accelerated material degradation in heritage buildings, where high temperatures and repeated thermal fluctuations can cause cracks and degrade the aesthetic quality of the colonial facades that are *Kayutangan*'s main attraction (Ismail, Samad, and Malek 2008).

Urban Heat Island Phenomenon

Analysis of Landsat 8 Collection 2 Level-2 satellite imagery from the advanced Google Earth Engine platform reveals significant fluctuations in Land Surface Temperature (LST) across the geographic area of *Klojen* District, a development area in Central Malang.

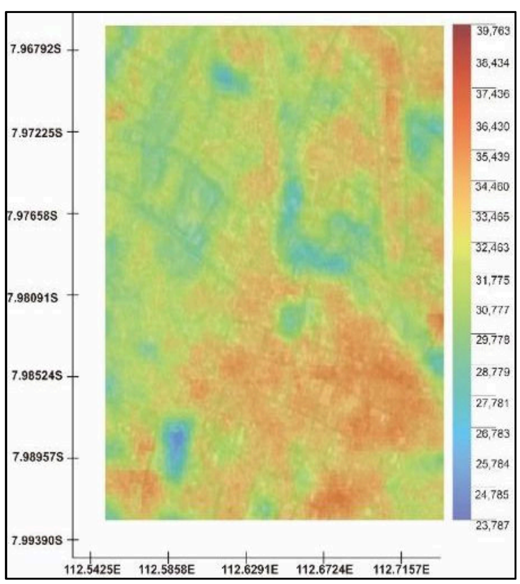

Figure 4. Heat map of *Klojen* District

Land surface temperature mapping in *Klojen* District shows regions characterised by extensive vegetation cover, including city parks, agricultural lands, and riverbanks, exhibit relatively lower temperature readings, ranging from 20 to 27°C. Meanwhile, densely populated areas dominated by complex infrastructure components such as residential areas, paved roads, and commercial areas recorded very high temperatures (orange to red), with land surface temperature (LST) increases of nearly 40°C (figure 4).

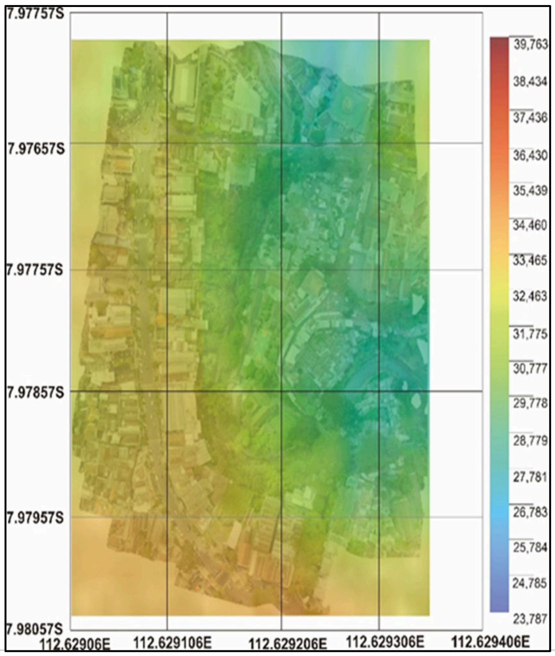

Figure 5. Heat map of *Kayutangan* Heritage Area

The analysis and comparison of relative thermal conditions between the Klojen District and the surrounding *Kayutangan* heritage area show that temperature fluctuations in the Klojen District range from approximately 23.8°C to a maximum of 39.7°C (figure 5). Meanwhile, temperature measurement data for the Kayutangan heritage area indicate a temperature range of 24°C to 32°C, categorized as a moderate temperature zone, which is lower than the temperature range observed in other commercial road corridors in Klojen, where temperatures can reach 26°C to 36°C. The warmest area in Klojen is the southwest, characterised by a concentration of commercial complexes and arterial roads, visually represented by a clear orange-red colour concentration on the temperature map.

Conversely, the coldest areas can be identified as dense patches of vegetation and adjacent river systems, typically depicted in blue, signifying their role as significant cold spots in the urban thermal landscape. A significant contributing factor to the temperature differences seen in the *Klojen* heat map (figure 5) can be attributed to the presence of low-rise historic buildings, such as those in the *Kayutangan* Heritage Area, which are surrounded by dense vegetation and massed structures; however, these structures do not reach the height of the newly developed Central Business District (CBD), which creates shade and thus reduces exposure to direct solar radiation.

The KHC Area is located near the Brantas Watershed, an ecological feature with the potential to be developed into a dedicated buffer zone to enhance environmental protection. In contrast, the modern commercial corridors that penetrate *Klojen* primarily comprise asphalt, concrete, and metal roofing, which absorb and retain heat for long periods, contributing to increased ambient temperatures (orange-red).

LST Characteristics of the study area

The LST analysis of the study area utilized satellite imagery data and on-site measurements, including dataloggers, to record surface temperature and humidity. Measurements were conducted in the *Kayutangan* Heritage Corridor, and the Buffer Zone temperature and humidity measurements in the study area were conducted in the morning from 6:00 to 7:00 AM, in the afternoon from 1:00 to 2:00 PM, and in the evening from 7:00 to 8:00 PM, with 300 measurements taken at 60 measurement points.

A comprehensive temporal analysis of Meteorology, Climatology, and Geophysics Agency (BMKG) data in *Klojen* District reveals a pattern of seasonal temperature variation. During the rainy season (November to April), the average LST tends to be significantly lower, ranging from 23°C to 30°C. Meanwhile, during the dry season (June-September), the average LST increases, with values exceeding 30°C. This significant temperature variation aligns with the characteristics of the rainy season climate in East Java, where solar radiation intensity increases significantly and cloud cover decreases drastically during the dry months.

Heat change trends based on satellite imagery analysis over the past few years indicate that Malang City has experienced an average LST increase of approximately one degree Celsius, particularly in areas dominated by built-up surfaces. This change was detected in the dense city centre, including the *Kayutangan* Heritage Area. Spatially, areas with vegetation cover tend to have lower LST, while main road KHC areas undergoing intensive urbanisation show consistent LST increases.

Therefore, conservation and revitalization efforts for *Kayutangan* heritage need to be synergized with microclimate mitigation strategies (Anon 2024; Zhang, Shi, and Chang 2022), particularly through the arrangement of green open spaces, strengthening buffer zones along the *Brantas* Watershed, the application of environmentally friendly materials in road pavements, effective vegetation management, and the development of blue spaces.

The Buffer zone characteristic

Buffer zones have more favorable micro-environmental characteristics, characterized by lower temperatures and higher humidity, compared to built-up areas. Integrating both characteristics (KHC and its buffer zones) into a single development unit requires an integrated approach. Understanding and analyzing surface thermal conditions, incorporating both into a unified analysis, is necessary to create comfortable urban spaces. Standards for comfortable temperature, humidity, and good air quality illustrate urban spatial comfort.

The ideal microclimate humidity for green open spaces varies by location and time, but typically ranges from 45% to 65% for human comfort (Sayad et al. 2024). More specifically, humidity can reach 58.3% to 72.2% during the day and morning in areas with dense vegetation, which helps minimize solar radiation. Green open spaces along riverbanks can be developed as buffer zones by incorporating blue spaces along the river, leveraging their potential for managing river flow (Respati Wikantiyoso 2010). Blue space development in the *Brantas* Watershed is carried out through the construction of small dams (Demuzere et al. 2014; Georgiou et al. 2021; Kozak et al. 2020; Labib, Lindley, and Huck 2020). In addition to its positive impacts, the construction of small dams also has adverse effects that must be addressed through physical and biotic interventions, as well as riparian management policies. One relevant mitigation approach is the riverbank buffer zone, also known as a riparian space, which serves as an environmental buffer and transitional area between KHC and urban ecological elements (Zhang et al. 2007).

LST Comparative Analysis of the KHC VS Buffer Zone Area

Based on temperature measurements in the *Kayutangan* heritage corridor, the characteristics of the corridor and buffer zone, as well as the LST characteristics of the study area, are illustrated in figures 6 and 7. The bar chart presented alongside this analysis effectively depicts the distribution of temperature ranges, including minimum, average, and maximum temperatures, clearly distinguishing between climatic conditions in the KHC and the buffer zone. For the KHC, the recorded temperature range was between 23.5°C and 39.6°C, with an average temperature calculated at 27.2°C. Meanwhile, in the buffer zone area, temperatures ranged from 20.6°C to 26.7°C, resulting in an average of 23.7°C (figure 6).

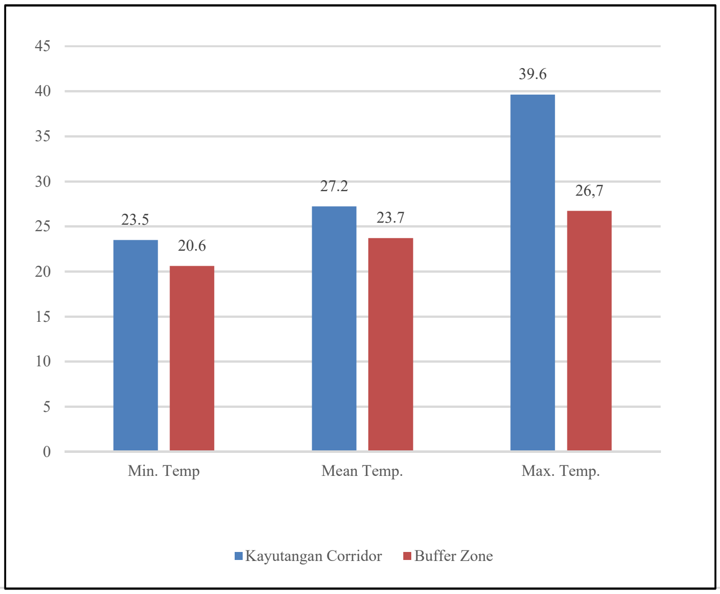

Figure 6. Temperature distribution frequency of KHC VS Buffer zone area

This graphical representation clearly shows that the KHC experiences more pronounced and extreme temperature variations, exhibiting higher peaks of heat that increase by an estimated 4 to 5 degrees Celsius compared to the relatively stable and moderate climate experienced in the buffer zone area. These observations imply that if development in the KHC is not effectively regulated, there is a significant risk of increased heat levels, requiring UHI-related interventions to mitigate potential adverse impacts on the environment and residents.

The histogram below (figure 7) illustrates the frequency distribution of various temperature zones within the KHC and the Buffer Zone. Specifically, the Buffer Zone area exhibits a distribution of temperature concentrations, with the majority of measurements falling within the range of 23.5°C to 23.5°C, covering approximately 73 measurement points across the entire area. In comparison, temperatures rarely exceed 26.1°C to 40°C, limited to only 25% (figure 7). This shows that, in general, the LST in the buffer zone area is lower. Conversely, the hot *Kayutangan* Heritage area shows a more dispersed temperature distribution, with a reasonably large segment in the range of 25.1°C to 38.9°C (moderate and high temperatures). This means that the distribution of hotspots is more even than in the Buffer Zone area.

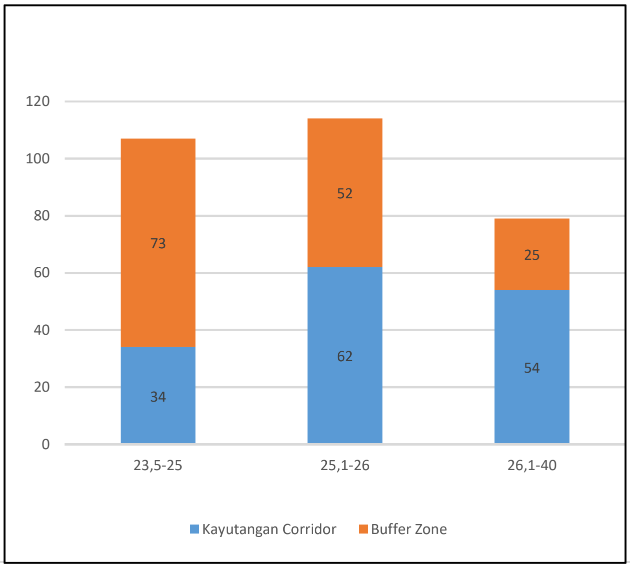

Figure 7. Temperature comparison of KHC VS Buffer zone area

CFD simulation approach

This model enables the simulation of existing conditions and the assessment of the impact of mitigation interventions on temperature distribution and airflow. Data on temperature, humidity, wind speed, and surface material characteristics are collected through field measurements, satellite imagery, and digital mapping (Haeri, Hassan, and Ghaffarianhoseini 2022; Norton et al. 2015). The CFD model is developed using a high-resolution mesh or grid with parameters that reflect real-world conditions. Simulations are conducted transiently to understand daily thermal fluctuations and the effectiveness of UHI mitigation strategies.

CFD-based simulation methods are approaches for modelling the dynamics of airflow and heat transfer in urban environments (Li et al. 2020). UHI mitigation methods are used to analyse the effectiveness of various interventions (increased green space, use of reflective materials, and optimisation of spatial planning to reduce the effects of warming). CFD works by numerically solving the Navier-Stokes equations and energy equations in complex urban domains. Kozak et al. (2020) stated that CFD methods can reproduce surface temperature distribution and airflow at the urban scale, providing insight into the impact of UHI mitigation interventions.

In this phase, CFD analysis was used to model the LST distribution, identify heat distribution patterns in Kayutangan, and determine the role of the buffer zone area. This analysis was then supported by narrative temperature distribution maps and a buffer zone intervention scheme, which provided recommendations for sustainable planning and development.

This CFD simulation analysis aimed to obtain an objective picture of heat and moisture distribution from 3D modeling of the existing area (the KHC and the buffer zone area) to determine future design interventions (Yang, Brumana, and Previtali 2019). With its water element (the *Brantas* River), the existing buffer zone was examined to determine its potential for development into a blue space area by expanding the river basin. The CFD profiles for two scenarios were generated by ignoring the presence of the river (which was not included in the 3D modeling) in the existing scenario. Scenario 2 included the river water surface as a cover parameter with a very low albedo (figure 8).

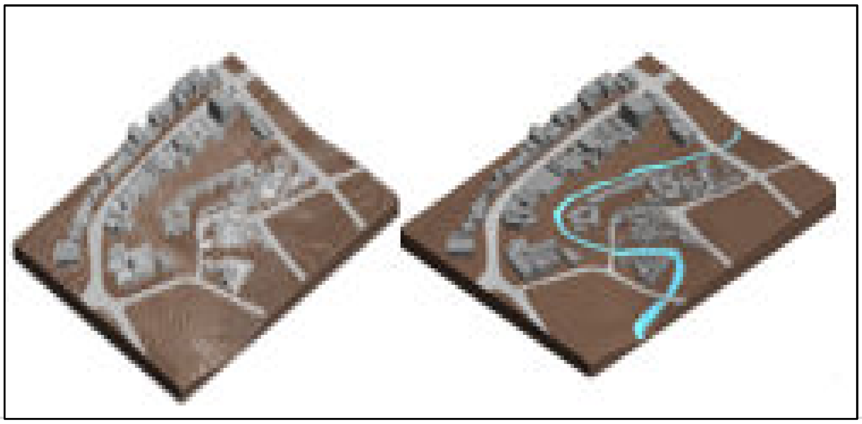

Figure 8. The 3D modelling of the study area scenario 1 and scenario 2

The temperature parameter used the temperature distribution from in-situ measurements. The input parameters in this scenario are differentiated only by the presence of rivers, to understand the role of rivers (water elements) in determining the design of interventions in the buffer zone area. The resulting steps are: (1) presentation of the temperature profile distribution in the area; (2) CFD simulation results in the existing area; and (3) blue space parameters.

CFD analysis results

CFD modeling results show significant differences in temperature distribution between the KHC area and the *Brantas* watershed buffer zone (figure 9). The measured temperature range in the simulation ranged from 20°C to 40°C. This analysis categorized the study area into two zones (Hot Zone and Cool Zone). The Hotspot Zone, situated along KHC, particularly the main road, which is characterized by dense buildings, exhibited the highest temperatures, ranging from 36 to 39°C.

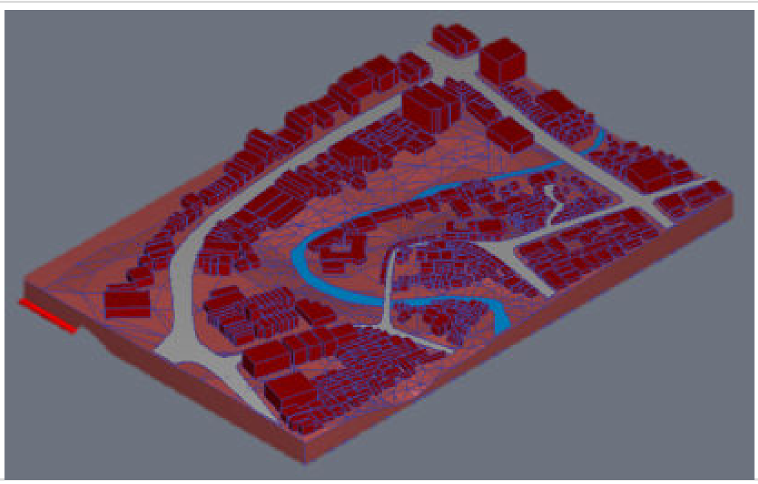

Figure 9. 3D modelling of the existing *Kayutangan* Heritage Area

The red-orange color on the CFD simulation result indicates heat accumulation due to the high density of hard materials (such as concrete, asphalt, and brick walls) and the lack of shade-providing vegetation. The narrow road morphology also restricts air circulation. Meanwhile, the Coolspot, a buffer zone characterized by vegetation around the *Brantas* watershed and splendid areas, exhibited a lower temperature distribution, ranging from 23 to 32°C (blue-green).

The *Brantas* watershed vegetation and green open spaces function as natural coolers, absorbing heat and increasing air humidity (Shareef 2022).

This indicates that the ecological buffer zone significantly suppresses the spread of UHI from the core of the KHC area. The resulting narrative temperature distribution map emphasizes the thermal gradient between the *Kayutangan* core and the buffer zone. Thus, the Buffer zone area acts as a thermal "lung" capable of maintaining the area's microclimate balance (Sharifi and Boland 2017).

Positive potential of the heritage area buffer zone

Several critical issues emerged from the analysis:(1) Urban Heat Island: Kayutangan exhibits micro-UHI conditions due to the dominance of heat-absorbing materials and limited open space. Heritage buildings that do not permit significant changes to their facades or structures also increase vulnerability to heat accumulation; (2) Buffer Zone Limitations: Although the *Brantas* watershed area plays an important role, the fragmentation of green open spaces due to land-use changes reduces the effectiveness of spatial cooling. Heat distribution still radiates to the KHC area; (3) Topographic and Morphological Influences: Regional elevation variations also influence heat distribution. Lower areas near the *Brantas* watershed tend to be cooler, while the KHC at higher elevations experiences heat accumulation. (4) Limitations of the CFD Model: This model relies on material assumptions (emissivity and thermal conductivity) that do not fully represent the conditions of degraded cultural heritage buildings.

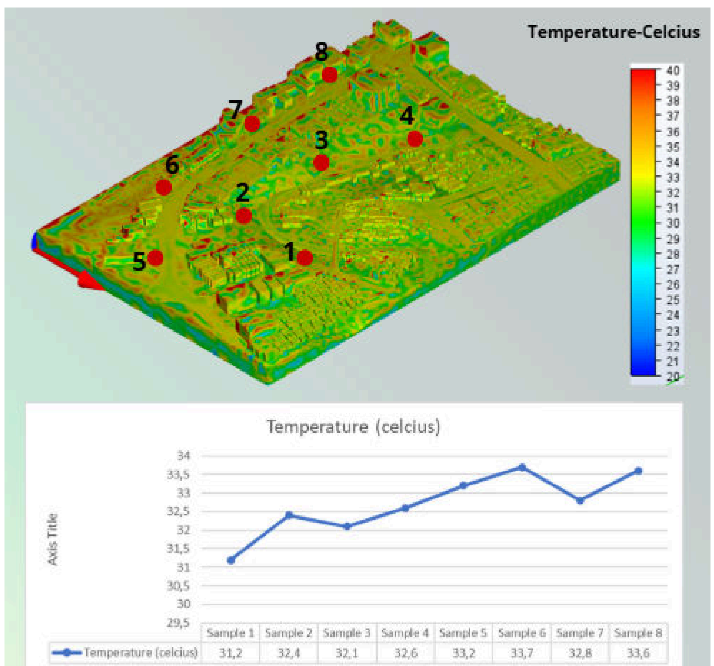

Figure 10. CFD simulation results of the existing areas

Furthermore, this simulation focuses on static heat distribution and does not fully account for cross-corridor wind flow, which impacts pedestrian thermal comfort (figure 10). Nevertheless, the CFD simulation analysis can be used as a tool to verify satellite imagery heatmap data and field measurements, which significantly confirm that the UHI phenomenon can be ecologically mitigated (Achim et al. 2012; Xiao et al. 2018).

The visualization scheme of the 3D simulation results for modeling the study area shows a direct relationship between the warm zone (the KHC area) and the cool zone (the buffer zone), which functions as an ecological connectivity area. Based on this analysis, the buffer zone area plays a significant role if design interventions are implemented as green open spaces and parks, with a dominant and proportional vegetation arrangement. The Brantas watershed has the potential to be developed as a blue space (figure

11) by increasing the volume of surface water inundation (Hansen et al. 2019; Kabisch, van den Bosch, and Lafortezza 2017).

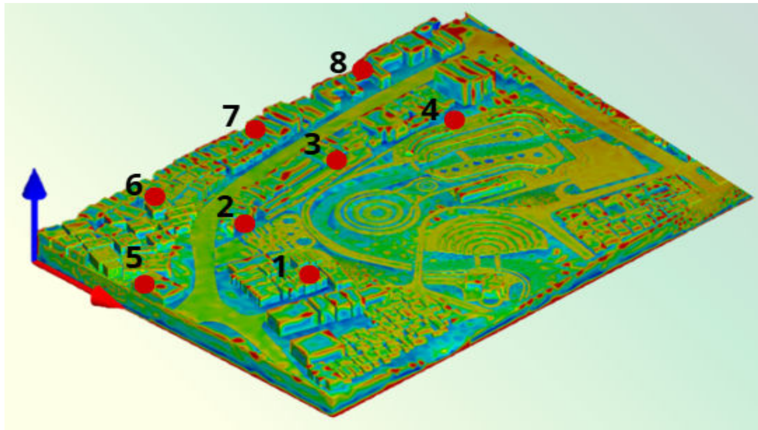

Figure 11. CFD simulation results with blue space scenario 3D modelling

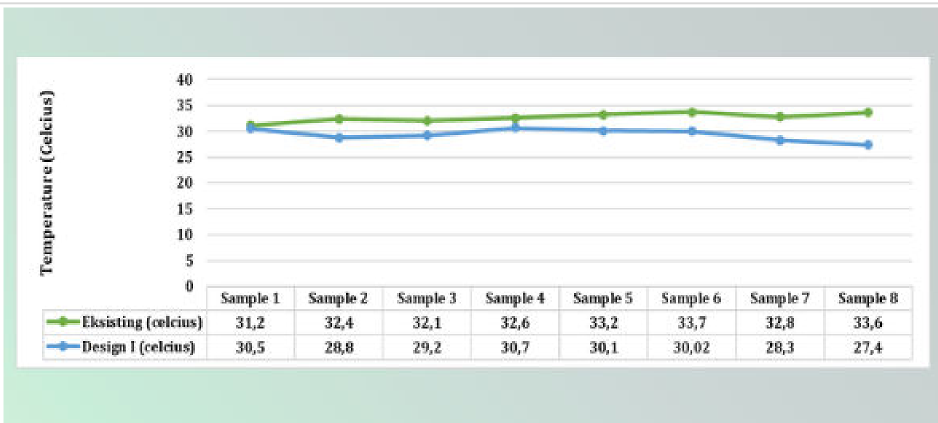

Figure 12. Comparison of surface temperature between existing conditions and buffer zone intervention

Figure 12 shows the results of the CFD simulation with the blue space design intervention scenario, which shows a difference in surface temperature between KHC (sample no. 5 – Sample no. 8) and the blue space surface temperature (sample no. 1 – sample no. 4), with a temperature decrease of between 1.5 and 5.2 degrees Celsius (see figure 11) In more detail, figure 12 illustrates the existing temperature decrease (green line) compared to the temperature in the blue space design intervention (blue line), with the following simulation results: Sample 1 decreased by 0.7°C; sample 2 decreased by 3.6°C; sample 3 decreased by 2.9°C; sample 4 decreased by 1.9°C; sample 5 decreased by 3.1°C; sample 6 decreased by 3.68°C; sample 7 decreased by 4.5°C; and sample 8 decreased by 5.2°C. These data show that design interventions, such as those in 3D modelling, succeeded in reducing the average temperature by 3.2°C.

One strategy to reduce microclimate pressures can be implemented by developing a buffer zone in the *Brantas* Watershed, considering that Malang City is a vital part of the *Brantas* River's upstream area. Buffer zones, particularly along the riverbanks and canals flowing near the *Kayutangan* cultural heritage area, serve as green belts that provide natural cooling through evapotranspiration, increase rainwater infiltration, and offer shade. Riparian vegetation with dense canopies can lower surface temperatures while improving air and water quality. The degradation of the *Brantas* River and its riparian areas can be addressed through buffer zone design interventions. Buffer zones play a crucial role in retaining sediment, filtering pollutants from surface runoff, and maintaining riverbank stability to prevent landslides or erosion (Cherrie et al. 2018).

Buffer zone intervention concept scheme

Based on the analysis and narrative map, a buffer zone intervention concept scheme was developed with four main strategies: (1) Optimisation of the KHC area: Use of reflective materials on new road surfaces and roofs (that do not violate cultural heritage regulations), addition of micro-scale vegetation (potted trees, lightweight roof gardens), and design of corridors with cross-ventilation to reduce heat accumulation; (2) Strengthening the *Brantas* Watershed Buffer Zone: Deforestation of riparian vegetation, development of linear parks along the river corridor, and integration of public green open spaces and blue spaces to increase heat absorption capacity. This buffer zone functions as a natural cooler and buffers the spread of UHI from the KHC area; (3) Enhancing the *Brantas* River as a Blue Space: To enhance further the role of the *Brantas* River and its water elements, the river can be developed into a blue space. This development concept still requires in-depth study through an Environmental Impact Analysis (EIA) study related to physical interventions within the river body. (4) Ecological Connectivity: Building ecological connections through greenways and open canals between the KHC and the Buffer zone area. This connectivity serves as a cooling corridor, supporting urban biodiversity (Rodríguez-Espinosa, Aguilera-Benavente, and Gómez-Delgado 2020; Capotorti et al. 2019; Jim 2013).

Kayutangan heritage conservation in integrated city development

The phenomenon of UHI in built-up urban areas requires serious attention in urban development policies. Revitalising the *Kayutangan* Heritage Area, with its rapidly increasing activity trend, will further increase LST, which needs to be mitigated through spatial planning policies that can function as a buffer zone for this area. According to Gehl (2010), the revitalisation of historic areas can be achieved by developing integrated tourism that is based on culture and the natural environment. Revitalisation through innovative use of public spaces, utilising rivers as blue spaces, pedestrian areas, and green open spaces, can improve the quality of life for city residents and mitigate the negative impacts of uncontrolled urbanisation (Litman 2013).

Urban revitalisation poses a significant challenge in urban planning, particularly amid policy fragmentation that hinders sustainable development. One increasingly adopted approach to address this challenge is integrated planning, which coordinates various stakeholder policies to balance economic, social, and environmental needs (Albrechts 2004).

Conclusions

The Urban Heat Island (UHI) phenomenon in the *Kayutangan* Heritage Area occurs in the context of intensive urban development and the impact of global climate change. Computational Fluid Dynamics (CFD) analysis results indicate that the area's temperature increase is significantly influenced by the limited availability of heat-resistant building materials and the lack of shading vegetation. This condition results in an uneven distribution of land surface temperatures (LST), indicating a decline in the region's microclimate balance. Therefore, ecological and conservation-based mitigation strategies are needed to restore environmental functions while maintaining the historical value of the heritage area.

The buffer zone of the Brantas Watershed plays a strategic role in stabilising the microclimate and reducing the intensity of the UHI effect in Kayutangan. Ecological integration can be achieved by strengthening the connectivity of blue and green spaces, which simultaneously improves thermal quality and enhances the area's visual aesthetics.

The development of blue spaces along the Brantas watershed, achieved through water volume optimisation and the implementation of small dams, has the potential to create a more balanced ecosystem. In addition to functioning as "cool islands", blue spaces also reinforce the identity of heritage landscape architecture as environmentally friendly and adaptive to climate change approaches.

Thus, the successful management of the Kayutangan Heritage Area depends heavily on the implementation of a collaborative and integrated development model that combines cultural heritage conservation with strengthening the ecological system of the buffer zone. This approach achieves a balance between historical preservation, thermal comfort, and urban climate resilience. Through this integrative strategy, Kayutangan can continue to develop as a sustainable and resilient historical area, serving as a best-practice example of climate mitigation-based heritage area revitalisation in Indonesia.

Ethics declaration

The authors declare no conflicts of interest in the publication of this paper.

Acknowledgments

This study was funded by the Ministry of Higher Education, Research, Science, and Technology of the Republic of Indonesia, whose support we gratefully acknowledge. We also extend our appreciation to the members of the Laboratory of Urban and Human Settlements, Department of Architecture, Faculty of Engineering, University of Merdeka Malang, as well as to all individuals who contributed to the Housing and Human Settlement project, particularly by providing supporting data.

Funding

This research was funded by the Ministry of Higher Education, Research, Science, and Technology of the Republic of Indonesia (0419/C3/DT.05.00/2025).

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