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Urbanization Analysis of Land Surface Temperature Modeling in the Peri-Urban of Surakarta

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ABSTRACT
The rapid development of urban areas characterized by urbanization has caused various impacts, such as LST. The Peri-Urban area of Surakarta City is one of the areas that experiences similar conditions. This study aims to measure urbanization through the urban form, population, and land urbanization and modeling urbanization of Land Surface Temperature. The method used in this study is modeling using Ordinary least squares (OLS) and Geographically Weighted Regression (GWR). Data processing tools to support this research are ArcGIS and Google Earth Engine. The combination of ArcGIS and Google Earth Engine makes LST modeling more accurate. The measurement results show that the urbanization rate in the peri-urban area of Surakarta City, based on the parameters of land urbanization and urban form, tends to move to the South and West sides with a higher population in areas close to Surakarta City. The results of this study show that GWR modeling is better at explaining the relationship of urbanization with LST than OLS models based on AICc numbers. The relationship of urbanization with population parameters, population density, percentage of built-up land, and urban form with LST using the GWR model of 66.17% and the OLS model reveals that urbanization.

INTRODUCTION

Cities are complex and dynamic structures whose growth and development have various factors (Jatayu, Saizen, Rustiadi, Pribadi, & Juanda, 2022). Urbanization is one of the factors of urban development. Urbanization as an inevitable socioeconomic development trend results in uncontrolled urban growth, such as the urban sprawl phenomenon (Liu et al., 2021; Lu, Song, & Lyu, 2022; N. Zhang et al., 2022) Half of the world's population lives in urban areas (Larsen, Yeshitela, Mulatu, Seifu, & Desta, 2019). The development of urban areas has a significant impact on the surrounding area (Klimanova, Illarionova, & Grunewald, 2021; Noviani, Ahmad, Sarwono, Sugiyanto, & Prihadi, 2022; Permatasari & Pradoto, 2019). Urban growth results in population growth in peripheral areas, so there is an increase in land demand and contributes to the formation of developed land (Buchori, Pangi, Pramitasari, Basuki, & Wahyu Sejati, 2020; Selang, Iskandar, & Widodo, 2018).

The essence of urbanization is Population urbanization and land urbanization (Shan et al., 2021). The built-up area is accurately related to urbanization (B. Zhang, Zhang, & Miao, 2022; J. Zhang, Zhang, Tan, & Yuan, 2022). Population urbanization refers to the process of moving people from rural to urban areas to integrate rural to urban populations, as experts use population numbers and population density to characterize population urbanization (Muta'ali, 2015; Qi, Han, & Kou, 2020; Shan et al., 2021). The rate of development of land urbanization is faster than population urbanization (Shan et al., 2021).

Surakarta City is the parent city of the SUBOSUKOWONOSRATEN area (Surakarta City, Boyolali Regency, Sukoharjo Regency, Wonogiri Regency, Karanganyar Regency, Sragen Regency, and Klaten Regency). The city of Surakarta and the surrounding area led to the formation of a metropolitan city due to high shuttle activities (Sugestiadi & Basuki, 2020). The development of Surakarta City has the most significant influence on the development of urban nature in the surrounding area (Kurnianingsih, Pratami, & Putri, 2021). The urbanization process accompanied by the action of Surakarta City outwards caused the peri-urban areas, namely Sukoharjo Regency, Karanganyar Regency, and Boyolali Regency, to get the most influence compared to other regions around Surakarta City (Mataufani, 2020; Na'imma, 2013). The development of urban areas spread to peri-urban areas, causing land fragmentation into small parts, which is one of the identifications of urban sprawl in the region (Mayca & Sri, 2015). The development of Surakarta City also encourages the increasing need for land and is the main factor in converting agricultural land into small and jumping parts (Noviani et al., 2022; Sugestiadi & Basuki, 2020). Peri-urban areas are generally formed due to urban expansion and tend to have a mixture of cities and villages that have not been organized and fragmented, and land cover patterns are fragmented, inefficient, unsustainable, and challenging to manage (Jatayu et al., 2022; Wandl & Magoni, 2017).

Sustainable development in suburban areas aims to make cities and settlements inclusive, safe, resilient, and sustainable by implementing the link between suburbs and urban regions through urban form analysis (Hosea, Pravitasari, Setiawan, & Rustiadi, 2019; Jatayu et al., 2022). Urban form analysis is an important design tool for examining the formation and development of the city's physical environment (Hermand & Quesada, 2019). An excellent urban form can combine the concepts of sustainability and resilience so that it can support urban functions. It can use resources sustainably and provide a solid economic base and a good quality of life for its residents to support the transition to a more resilient, healthy, and sustainable city (Jatayu et al., 2022; Mcgranahan & Satterthwaite, 2014). An excellent urban form can combine the concepts of sustainability and resilience so that it can support urban functions and can use resources sustainably, provide a solid economic base and a good quality of life for its residents to support the transition to a more resilient, healthy, and sustainable city (Jabareen, 2006; Su & Qi, 2023). Urbanization is closely related to urban form because one indication is that built-up land is increasing and causing changes in urban structure that will affect the urban form.

Global large-scale urbanization significantly impacts climate change for sustainable development, especially by destroying regional thermal environments in urban agglomerations (Chen, Zhou, Hu, & Zhou, 2020; N. Zhang et al., 2022). Land cover change highly depends on urbanization (Xiong et al., 2022). Under the development trend of cities, more and more people will live in sub-centers, and the heat stress experienced by residents in significant centers and sub-centers will inevitably be different (Su & Qi, 2023). The urbanization process has created thermal mass heterogeneity that changes the microclimate conditions of urban environments. The response of urban planning and design to urban microclimates is critical to creating a sustainable urban environment (Lin, 2021). Urban form can explain Land surface temperature (LST) (Guo, Han, Xie, Cai, & Zhao, 2020; S. Zhang & Wang, 2021). Urban form due to population growth and population density resulting from urbanization affects Land Surface Temperature. Urban form and LST correlate positively (Su & Qi, 2023). The urban form in big cities is generally compact. The compact urban form has a large population with short transportation and communication distances, thus benefiting infrastructure efficiency (Yan et al., 2021). Urbanization will indirectly create a compact urban form. Compact urban conditions produce higher Land Surface Temperatures (Lin, 2021; Yan et al., 2021).

This study aims to see urbanization through the urban form, population, and land urbanization and model urbanization of Land Surface Temperature. LST calculations use remote sensing and mapping the heat energy released by the atmosphere from the Earth (Çolakkadioğlu, 2023). Google Earth Engine is a supporting tool for accurately calculating LST (Ullah et al., 2023). Population and population density are the basis for population urbanization (Muta'ali, 2015; Qi et al., 2020; Shan et al., 2021). LULC determination is the basis for calculating the percentage of built-up land in land urbanization. Metrics are the basis for determining urban form (N. Zhang et al., 2022). The influence of urbanization on LST is determined through modeling using the Ordinary Least Square (OLS) and Geographically Weighted (GWR) Regression methods so that comparisons and distribution emerge.

RESEARCH METHODS

Study Area

This research is in the Peri-Urban Area, directly adjacent to Surakarta City. Three regencies adjacent to Surakarta City are Karanganyar Regency, Sukoharjo Regency, and Boyolali Regency. In more detail, this research is in 8 sub-districts of 3 regencies. Karanganyar Regency includes Jaten District, Gondangrejo District, and Colomadu District. Sukoharjo Regency, Kartasura District, Baki District, Grogol District, and Mojolaban District. The third district is Boyolali District, namely Ngemplak District. This research uses a saturated sample so that the entire village or entire population is the sample. This study has a total location of 99 villages. Surakarta City is one of the major cities in Central Java, which is currently experiencing rapid development and, together with the surrounding area, towards the metropolitan direction (Noviani et al., 2022; Putra, Sukmono, & Sasmito, 2018; Sugestiadi & Basuki, 2020).

Data and Data Sources

This study used primary and secondary data to determine urban form using land cover analysis. Primary data functions include land cover classification through image analysis and field surveys. Secondary data collection uses institutional methods through several institutions. Table 1 shows the data and data sources in this study.

Table 1. Data and Data Sources

Data	Unit	Data Sources
Number of Village-Level Population	Soul	Badan Pusat Statistik
Area at Village Level	Km^2	Badan Informasi Geospasial
Population Density	Soul/ Km^2	Researcher Analysis
Landsat 8	Pixel	USGS
Land Use Land Cover	Pixel	Researcher Analysis
Percentage of Built-up Land	%	Researcher Analysis
Urban Form	Compact/Fragmented	Researcher Analysis

(Source: Researcher Analysis, 2023)

Method

Urbanization

Urbanization is a natural, historical process in which non-agricultural industries converge in cities, and rural populations are concentrated in cities as industrialization develops (Lyu, 2023). The essence of urbanization is population urbanization and land urbanization (Shan et al., 2021). Population numbers and population density characterize urbanization (Muta'ali, 2015; Qi et al., 2020; Shan et al., 2021). The built-up land composition indicates urban areas (N. Zhang et al., 2022). Changes in the shape of cities are also an indication of urbanization (Yan et al., 2021). There are four main parameters in determining urbanization in this study, namely the number of populations, population density, percentage of built-up land, and urban form (Table 2).

Table 2. Indicators and Parameters of Urbanization

No	Indicator	Parameter	Assumption
1	Population Urbanization	Population (Muta'ali, 2015; Qi et al., 2020; Shan et al., 2021).	Urban areas have a higher population compared to rural areas.
		Population Density (Muta'ali, 2015; Qi et al., 2020; Shan et al., 2021).	Urban areas have a higher population density compared to rural areas.
2	Land Urbanization	Percentage of Built-up Land (Lin, 2021; B. Zhang et al., 2022; J. Zhang et al., 2022; N. Zhang et al., 2022)	The higher the percentage of built-up land, the more urban the area is or has a high level of urbanization.
3	Urban Form	Compact Urban Form (Lin, 2021; Yan et al., 2021)	The compact urban form indicates higher urbanization.

Source: (Lin, 2021; Muta'ali, 2015; Qi et al., 2020; Shan et al., 2021; Yan et al., 2021; B. Zhang et al., 2022; J. Zhang et al., 2022; N. Zhang et al., 2022)

Population Urbanization

Population Urbanization consists of two parameters, namely Population Number and Population DensityThe source of population data is the Badan Pusat Statistik. Population density is the result of comparing the population per 1 km² (Christiani, Tedjo, & Martono, n.d.; Muta'ali, 2015). The population density formula is as follows (1):

$$PD = \frac{P}{A} \quad (1)$$

Information:
PD = Population (Soul/ Km²)
P = Population (Soul)
A = Area (Km²)

Land Urbanization

The parameter of Land Urbanization is the percentage of built-up land (Lin, 2021; B. Zhang et al., 2022; J. Zhang et al., 2022; N. Zhang et al., 2022). Land urbanization is the change from agricultural to non-agricultural land cover (B. Zhang et al., 2022). Built-up areas are an accurate indicator in assessing the urbanization process (J. Zhang et al., 2022). The percentage of built-up land will be determined, starting from the Land Use Land Cover (LULC) classification. LULC classification using Google Earth Engine with code (2):

https://bit.ly/LULCCode (2)

The dataset for LULC classification is USGS Landsat 8 with a combination of bands 1-7, which has the highest accuracy compared to other band combinations (Fariz, Suhardono, Sultan, Rahmawati, & Arifah, 2022). The cloud-based Google Earth Engine (GEE) platform is helpful for the analysis of large spatial areas using high-performance computing resources without the need to download data and can be used as filters for imagery with little cloud cover (Floreano & de Moraes, 2021; Pande et al., 2023; Gandharum et al., 2022). LULC validation in this study used the KAPA index. Confusion matrix and Kappa coefficients are standard for assessing image accuracy and have been used in numerous land classification studies (Rwanga & Ndambuki, 2017). Determination of accuracy test samples requires a minimum of 10n to 100n pixels, where n is the number of bands combined in the land use classification (Wulansari, 2017). The kappa coefficient is perfect when the result approaches 1 and decreases further to 0 (Rwanga & Ndambuki, 2017). The accuracy value of the Kappa Coefficient that is feasible and acceptable for accuracy is 0.80-0.85 (80%-85) (Wulansari, 2017). The validation result of the kappa coefficient for land cover in this study was 0.94 (94%), so the data produced was valid. The percentage of built-up land is measured using the formula (3):

$$BL = \frac{\text{BLA}}{\text{A}} \text{ x } 100 \quad (3)$$

Information:
BL : Percentage of Built-up Land (%)
BLA : Built-up Land Area (Km^2)
A : Area (Km^2)

Urban Form

Urban forms are analyzed using urban form calculations with spatial metrics or landscape metrics approaches, which are analyzed using FRAGSTAT software through land cover raster data in the peri-urban area of Surakarta City. Spatial Metrics is one of the most prominent methods in landscape quantification and has been the basis for developing other methods (Jatayu et al., 2022). In addition to measuring spatial patterns and forms, The Spatial Metrics approach can measure changes in land cover and identify regional shapes and regional expansion phenomena (Hosea et al., 2019). The Spatial Metrics approach can measure and explain spatial structure in various ways at the patch, class of patch, and landscape levels (Jatayu et al., 2022). The Spatial Metrics approach can also analyze an area's shape in a time series to identify trends in the development of an area (Hosea et al., 2019). The selection of the spatial matrix uses four indicators of sustainable city form, namely compactness (PD and SHAPE), contiguity (CONTIG and COHESION), connected (SPLIT and MESH) (Jatayu et al., 2020; Hosea et al., 2019) and diversity (SIDI). In this study, the most frequently used metric from a landscape perspective is the urban form indicator (N. Zhang et al., 2022)to better understand the urban form. Table 3 shows the classification of compact city forms, and Table 4 shows the matrix characteristics of sustainable urban forms.

Table 3. Matrix Value Limit of Compact City Form

Parameter	Limit	Urban Form
Patch Density (PD)	<100	Compact
Shape Index (SHAPE)	= 1	Compact
Contiguity Index (CONTIG)	> 0,5	Compact
Cohesion Index (COHESION)	> 50	Compact
Mesh (MESH) & Split (SPLIT)	Mesh > Split	Compact
Shimpson's Diversity (SIDI)	> 0,5	Compact

Source: (Hosea et al., 2019; Jatayu et al., 2022)

Table 4. Matrix Characteristics of Sustainable Urban Form

Indicator	Matrix	Formula	Description
Compactness	Patch Density (PD)	$PD = \frac{n_i}{A}(10,000)$	The number of patches of class i is divided by the entire landscape area, describing landscape density, where ni is the number of patches of class i, and A is the same as above; the unit is the number per square kilometer, PD > 0.
	Shape Index (SHAPE)	$SHAPE = \frac{P_{ij}}{min\ P_{ij}}$	SHAPE equals patch perimeter (given in the number of cell surfaces) divided by the minimum boundary (shown in the number of cell surfaces) possible for a maximally compact patch (in a square raster format) of the corresponding patch area, where pij is the perimeter of patch ij. SHAPE 1, without limit. SHAPE = 1 when the patch is maximally compact (i.e., square or almost square) and increases without limit as the patch shape becomes more irregular. The SHAPE index describes the irregularity of the shape/form of a class.

Indicator	Matrix	Formula	Description
Contiguity	Contiguity Index (CONTIG)	$CONTIG = \frac{\left[\frac{\sum_{r=1}^{n} c_{ijr}}{a_{ij}}\right]-1}{v-1}(100)$	Measure spatial connectedness, or contiguity of cells within a grid-cell patch in a 3×3pixel template. Where cijr is the neighborhood value of pixel r in patch ij, v is the sum of the values in a 3-by-3 cell template, and aij is the area of patch ij in terms of the number of cells. Large contiguous patches will result in larger contiguity index values.
	Cohesion Index (COHESION)	$COHESION = \left[1 - \frac{\sum_{j=1}^{n} p_{ij}}{\sum_{j=1}^{n} p_{ij}\sqrt{a_{ij}}}\right]\left[1-\frac{1}{\sqrt{A}}\right]^{-1}(100)$	Measures the physical connectedness of patches, where pij is the perimeter of patch ij; aij is the area of patch ij; n is the total number of patches in the landscape; and A is the entire landscape area; the unit is percent, 0 < COHESION ≤ 100. Patch cohesion increases as the patch type becomes more clumped or aggregated in its distribution and, hence, more physically connected.
Connected	Split Index (SPLIT)	$\frac{A^2}{\sum_{j=1}^{n} {a_{ij}}^2}$	The area squared of the entire landscape divided by the area squared of all patches in type i, describing landscape fragmentation, which is equivalent to A/MESH and can be understood as the number of effective mesh, where aij, A, and n are the same as above; it is dimensionless, 1 SPLIT the number squared of grids in the entire landscape. Higher SPLIT values indicate higher fragmentation.
	Mesh Index (MESH)	$\frac{\sum_{j=1}^{n} {a_{ij}}^2}{A}(100)$	The area squared of all patches in class i divided by the entire landscape area (km2), describing landscape fragmentation, where aij, A, and n are the same as above; the unit is hectare, the ratio of cell size to landscape area MESH the entire landscape area (A). Lower MESH values indicate higher fragmentation.
Diversity	Shimpson's Diversity Index (SIDI)	$SIDI = 1 - \sum_{i=1}^{m} P_i^2$	0 ≦ SIDI < 1 SIDI = 0 when the landscape contains only 1 patch (i.e., no diversity). SIDI approaches 1 as the number of different patch types (i.e., patch richness, PR) increases, and the proportional distribution of area among patch types becomes more equitable.

Source: (Hosea et al., 2019; Jatayu et al., 2022)

Land Surface Temperature

Land Surface Temperature (LST) calculation using Google Earth Engine with code (4):

https://bit.ly/LSTCode (4)

Determination of Land Surface Temperature (LST) in this research uses remote sensing methods via Landsat 8 imagery ((Hidayati & Suharyadi, 2019). The dataset used in determining LST in this study is USGS Landsat 8. The bands used in the LULC classification are a combination of bands 2-6 and Band 10. Google Earth Engine can analyze changes in LST patterns over time (Latue, Rakuasa, Somae, & Muin, 2023).

Urbanization Modeling with Land Surface Temperature

Urban agglomerations face regional thermal environmental deterioration (N. Zhang et al., 2022). Modeling urbanization relationships consisting of 3 indicators with four parameters with LST was carried out using the Ordinary least squares (OLS) and Geographically Weighted Regression (GWR) methods. Non-spatial models such as OLS cannot adequately capture the local relationships that are inherently present in spatial variables (Njoku & Tenenbaum, 2022). GWR can perform demographic prediction analysis (Carlucci & Salvati, 2023). OLS and GWR are the most widely used methods in various research fields (Isazade, Qasimi, Dong, Kaplan, & Isazade, 2023). OLS and GWR are used to perform predictive analysis and relationship modeling from demographic cases, LULC, and Land Surface Temperature (Carlucci & Salvati, 2023; Isazade et al., 2023; Njoku & Tenenbaum, 2022). In this study, the analysis using OLS and GWR aims to compare the two methods to determine the best method to determine the relationship between Urbanization and Land Surface Temperature. The analysis process uses the ArcGIS Program with "Ordinary least squares (OLS) and Geographically Weighted Regression (GWR)" tools. Figure 1 shows in detail the flow in this study.

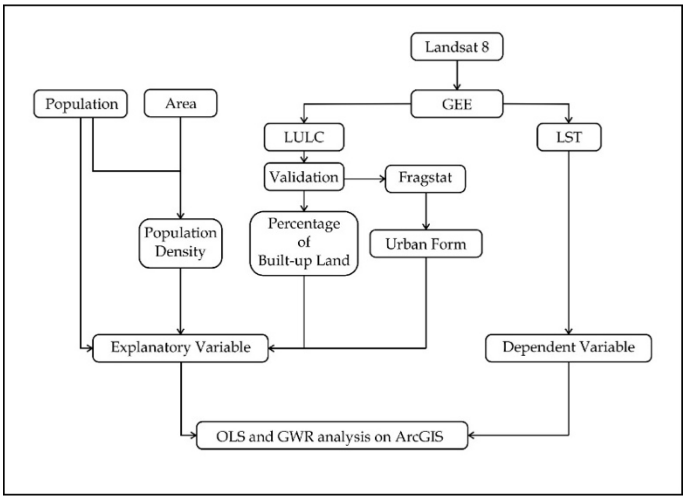

Figure 1. Matrix Value Limit of Compact Urban Form (Source: Research Analysis, 2023)

RESULTS AND DISCUSSION

Urbanization

This study aims to see urbanization through the form of cities, population, and land urbanization and modeling urbanization of Land Surface Temperature. Urbanization is determined based on three indicators: Population Urbanization, Land Urbanization, and Urban Form. Population Urbanization has parameters of population number and population density. Land urbanization results from the percentage of land built, while urban forms come from matrix analysis of processing results in Fragstat software. Table 5 shows the data processing results from urbanization and LST analysis.

Table 5. Matrix Characteristics of Sustainable Urban Form

Peri-Urban Area Surakarta City	Max	Min	Average
Population (soul)	24,556	2,124	7,535
Population Density (soul/km²)	622	13,137	1,082
Built-up Land Percentage (%)	26.23	100	76.39
Land Surface Temperature* (°C)	32.26	19.79	25.8
	Compact	Fragmented	
Urban Form	4	4	

*Dependent Variable

Source: Researcher Analysis, 2023

Population Urbanization

Some experts use population and population density to characterize population urbanization (Muta'ali, 2015; Qi et al., 2020; Shan et al., 2021). Based on Table 5, the average village-level population in the Peri-Urban Area of Surakarta City is 7,535 people. The largest population in the Peri-Urban Area of Surakarta City is 24,556 in Ngringo Village, Jaten District, and 21,471 in Cemani Village, Grogol District. The smallest population in the Peri-Urban Area of Surakarta City is Gajahan Village, Colomadu District, with 2,124 people, and Tegalmade Village, Mojolaban District, with a population of 2,231. Figure 2a shows that villages near or directly adjacent to Surakarta City tend to have a higher population. The population condition in the Peri-Urban Area of Surakarta City is due to the impact of urban development. The urban population explosion is not the result of high fertility but the flow of urbanization (Winayanti, 2016). The population explosion will lead to land urbanization. Population growth in peripheral areas has the most significant contribution to the formation of developed land (Selang et al., 2018).

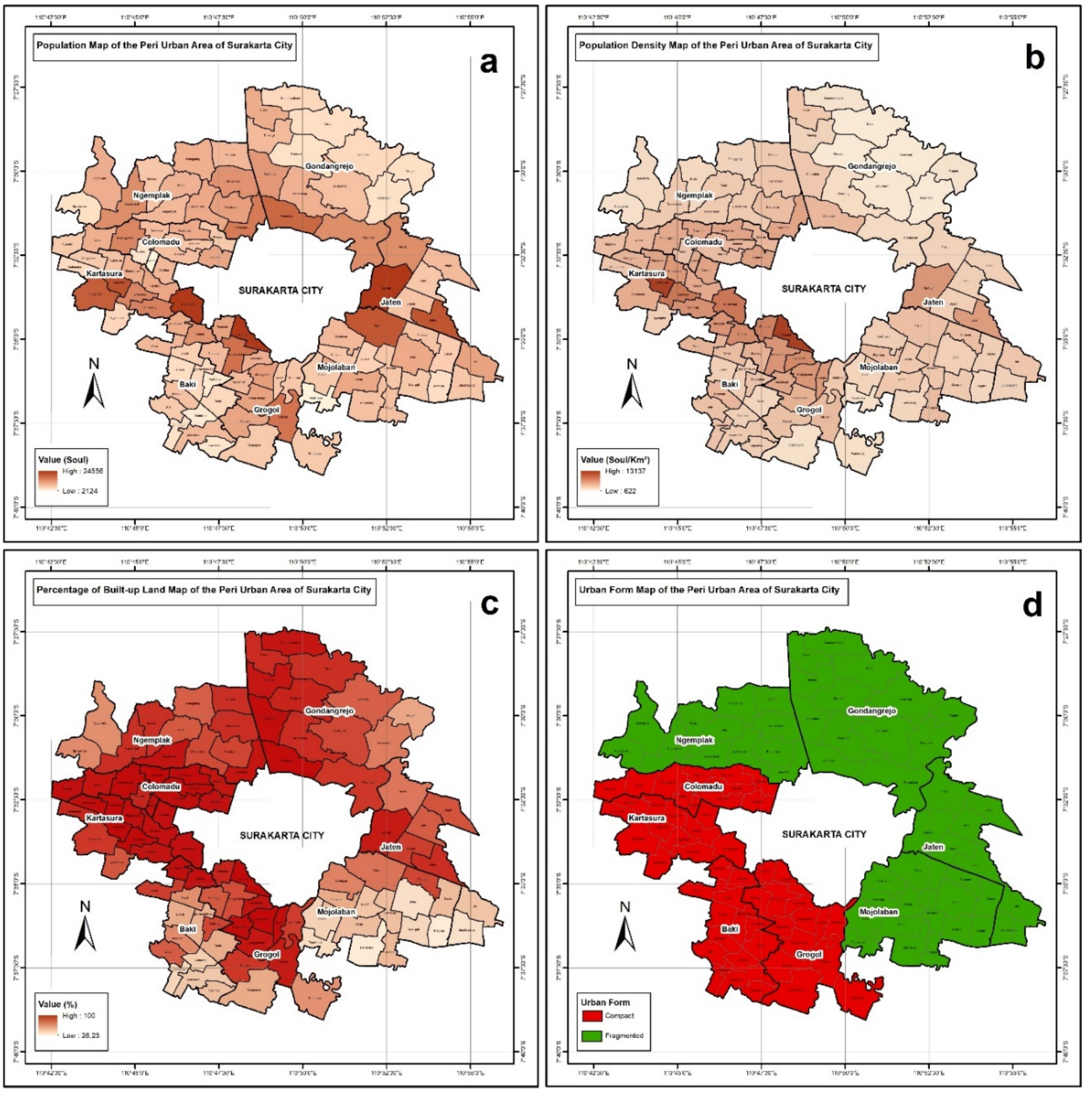

Figure 2. Urbanization Parameter Map (Source: Research Analysis, 2023)

Population urbanization does not only come from population but from population density. Population density is one indicator of urbanization —population density results from comparing population and area (Christiani et al., 2014). Areas with high populations do not mean that they have a high population density because they also have to look at the area. The high population density in the Peri-Urban area of Surakarta City tends to spread towards the south and west (Figure 2b). Based on Table 5, the average population density in the Peri-Urban Area of Surakarta City is 1,082 people/km². Cemani Village, Grogol District, has the highest population density, at 13,137 people/km². Cemani Village tends to have a high population because it is one of the villages with the largest population in the Peri-Urban Area of Surakarta City and a relatively small area. On the other hand, the area with the smallest population density is Dayu Village, Gondangrejo District, with a population density of 622 people/km². Areas with high population densities tend to have high rates of urbanization. According to the statement (Mardiansjah, Handayani, &; Setyono, 2018; Muta'ali, 2015), population density is one indicator of urbanization around Surakarta City.

Land Urbanization

Surakarta City is one of the big cities that is experiencing rapid development. (Putra et al., 2018). The increase in population in the Peri-Urban area of Surakarta City has an impact on increasing built-up land. Population growth in peripheral areas significantly contributes to the formation of developed land (Selang et al., 2018). Urbanization will undoubtedly encourage the conversion of non-developed land into built-up land, which causes land urbanization. Land urbanization is the change from agricultural to non-agricultural land cover (B. Zhang et al., 2022). The percentage of built-up land is one indication of urbanization. Lin, 2021 revealed that an increase in the percentage of built-up or urban land characterizes urbanization. The pace of development of land urbanization tends to be faster than population urbanization. The Peri-Urban Area of Surakarta City has an average percentage of built-up land of 76.39% (Table 5). The southern and western regions of Surakarta City tend to have a higher percentage of built-up land compared to the other areas. The condition of population density and the percentage of built-up land that tends to be higher to the west and south indicates that the development of Surakarta City tends to the west and south (Fig. 2c). The results of research on the development of Surakarta City in this study are by statements from (Mardiansjah et al., 2018; Mayca &; Sri, 2015) that the development of Surakarta City tends to the west and south, but more intensively in the south. The largest percentage of built-up land in the Peri-Urban Area of Surakarta City is Kartasura Village, Kartasura District, at 100%, while the smallest percentage is in Bekonang Village, Mojolaban District, with 25.70%.

Urban Form

The urban form in this study is divided into two: compact and fragmented. Urban form analysis is carried out at the sub-district level to broadly see the urban conditions in the Peri-Urban Area of Surakarta City. Urban form analysis is an important design tool for examining the formation and development of the city's physical environment over time (Hermand &; Quesada, 2019). City cohesiveness is one of the indicators of Urbanization (Lin, 2021) the determination of urban form in the Peri-Urban Area of Surakarta City using the spatial metrics method through Fragstat software. The results of Fragstat software processing are presented in Table 6 and Table 7, showing the urban forms in the Peri-Urban Area of Surakarta City.

Table 6. Matrix Processing Results Using FRAGSTAT

District	Spatial Metrics Value (%)						
	SHAPE	PD	CONTIG	COHESION	MESH	SPLIT	SIDI
Baki	1.2468	54.6648	0.6380	99.2912	62.2185	3.6517	0.5787
Grogol	1.3032	108.886	0.6062	98.0249	14.1547	21.995	0.7580
Mojolaban	1.2093	173.612	0.4539	98.2185	16.2067	23.162	0.6720
Jaten	1.2176	217.396	0.2800	98.1698	12.0463	22.376	0.6570

District	Spatial Metrics Value (%)						
	SHAPE	PD	CONTIG	COHESION	MESH	SPLIT	SIDI
Gondangrejo	1.1936	105.924	0.3750	97.9859	15.7444	38.802	0.7205
Ngemplak	1.1752	290.545	0.3456	96.367	53.4909	75.932	0.7753
Colomadu	1.2753	85.5528	0.6501	98.5286	23.6617	7.3802	0.6741
Kartasura	1.2558	246.187	0.6215	98.819	28.3322	7.6186	0.6563

Source: Researcher Analysis, 2023

Table 7. Urban Form in the Peri-Urban Area of Surakarta City in 2023

No.	District	Urban Form
1	Baki	Compact
2	Grogol	Compact
3	Mojolaban	Fragmented
4	Jaten	Fragmented
5	Gondangrejo	Fragmented
6	Ngemplak	Fragmented
7	Colomadu	Compact
8	Kartasura	Compact

Source: Researcher Analysis, 2023

Table 6 shows four compact districts and four fragmented urban forms in the Peri-urban area of Surakarta City. Just like the condition of population urbanization and land urbanization where the development of Surakarta City tends to the south and west, the shape of the urban form experiences similar things where districts with compact urban forms are in Grogol, Baki, Kartasura, and Colomadu Districts (Fig. 2d and Table 7). The condition of the urban form of the Surakarta City Peri-Urban area increasingly shows the development of Surakarta City towards the south and west.

Land Surface Temperature

The increase in developed land in urban areas will increase the value of LST. The loss of vegetation contributes to rising air and surface temperatures in urban areas (Prastyo, Nurjani, &; Giyarsih, 2022). Areas with high built-up land generally have higher surface temperatures than other regions. **Table 5** shows that the average LST in the Peri-Urban Area of Surakarta City is 25.8°C. In the Peri-Urban Area of Surakarta, the maximum surface temperature value is 32.26°C, while the lowest is 19.79°C. The average LST in each village was also calculated in this study. The village with the highest average LST is Madegono Village, Grogol District, with 28.86°. Cemani Village has land and increased population urbanization and has a high LST of 27.70°C. The lowest average LST value is in Dayu Village, Gondangrejo District, with a value of 24.18°C. The distribution of LST in the Peri-Urban Area of Surakarta City tends to be higher in the West and South regions. Southern conditions are hotter than other regions (**Fig. 3**). Land Surface Temperature (LST) plays an important role in the study of climate, air temperature, and urban environments on a local and global scale. (Hidayati &; Suharyadi, 2019). The process of urbanization has created heterogeneity of thermal mass, surface roughness, albedo, etc., which changes the microclimatic conditions of the urban environment (Lin, 2021). Areas with high LST tend to have higher urbanization.

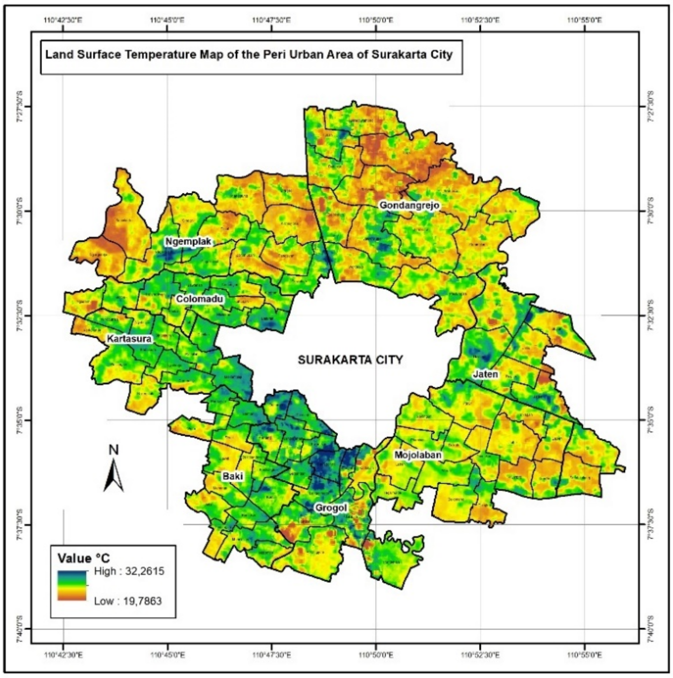

Figure 3. Land Surface Temperature Map (Source: Research Analysis, 2023)

Modeling the Relationship between Urbanization and Land Surface Temperature

Urbanization encourages increasing land cover change from non-built-up to built-up. These changes will increase land surface temperature. Urbanization in this study uses three indicators, namely population urbanization, land urbanization, and urban form. Population urbanization uses the parameters of population number and population density. Land urbanization uses the parameter of the percentage of built-up land. Urban forms use landscape-based matrix processing through Fragstat software. Modeling the relationship of urbanization to land surface temperature in this study uses Ordinary least squares (OLS) and Geographically Weighted Regression (GWR) models to see the difference between the two methods. Based on the results of processing through ArcGIS software between explanatory variables and dependent variables, R^2 results are obtained that show the relationship between variables. The processing results are shown in Table 8.

Table 8. OLS and GWR Results

Model	Number of Observation	R^2 (%)	R^2 Adjusted (%)	AICc
Ordinary least squares (OLS)	99	61.17	59.52	168.20
Geographically Weighted Regression (GWR)	99	70.48	66.17	155.41

Source: Researcher Analysis, 2023

Table 8. Showing the results of urbanization modeling with LST in the Peri-Urban area of Surakarta City using OLS and GWR models. Relationship modeling using 99 villages in the Peri-Urban area of Surakarta City. The results show that the GWR model residue is smaller than the OLS model. The number from Akaike's Information Criterion (AICc) shows the amount of residue, so if the AICc has a

smaller number, the better the model is used to measure variable relationship modeling. The GWR model shows an R^2 adjusted result of 66.17%, which shows that urbanization variables consisting of parameters of population, population density, built-up land, and urban form can explain LST; other factors explain the remaining 33.83%. The modeling results using GWR show a relationship between urbanization and LST, meaning that the higher the level of urbanization, the higher the LST. The OLS model reveals that urbanization can account for LST by 59.52%, which is smaller than the GWR model. The results from OLS are no better than those of using GWR based on the results from AICc. Spatially, the residue is shown in Figure 4.

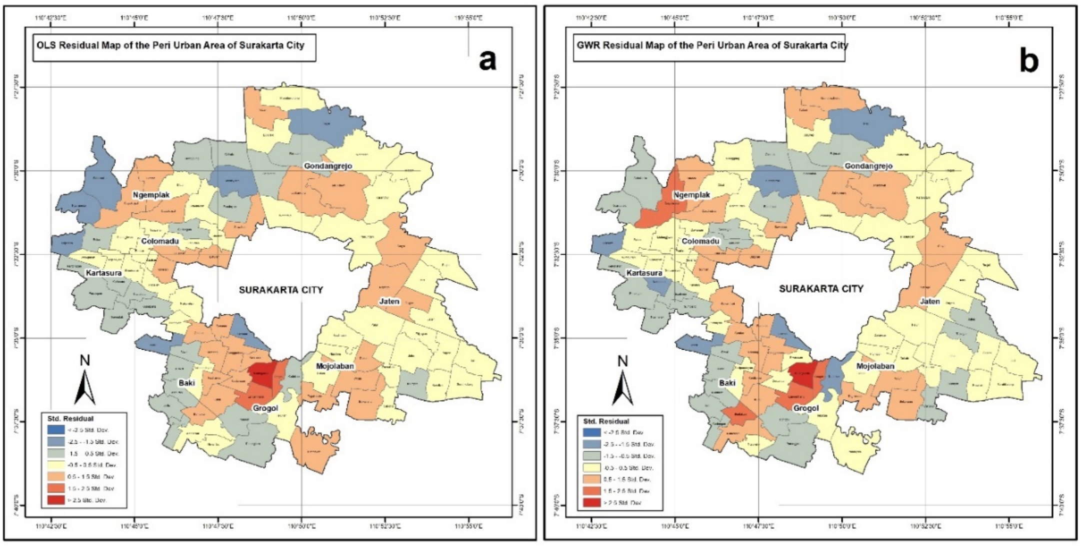

Figure 4. Residual Map of OLS and GWR (Source: Research Analysis, 2023)

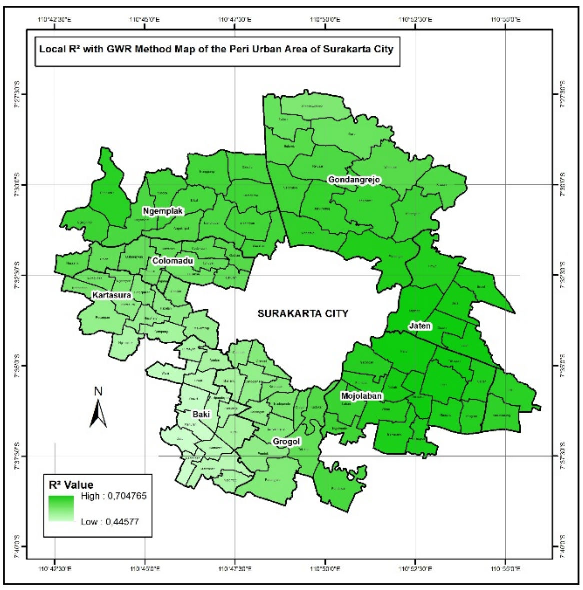

Figure 5. GWR Local Map (Source: Research Analysis, 2023)

Figure 4a shows the residual results of OLS, while Figure 4b. shows the residual results of GWR modeling—the lower the residual value (close to 0), the better the relationship between urbanization and LST. GWR can also describe relationships locally, so it can be said that in terms of describing relationships spatially, GWR is better than OLS. The GWR relationship locally is shown in Figure 5.

Figure 5 shows the relationship between urbanization and LST by R^2 in each village using the GWR model. The most significant relationship is 0.7048 or 70.48%, and the smallest relationship is 0.4458 or 44.58%. The results of this research show that urbanization in the Peri Urban Area of Surakarta City has resulted in an increase in thermal conditions which is in accordance with research in other large cities. Urbanization in the urban area of Surakarta City causes thermal increases in suburban areas. The urbanization process has created thermal mass heterogeneity that changes the microclimate conditions of the urban environment (Lin, 2021). Urbanization in the Peri-Urban area of Surakarta City also makes thermal conditions hotter due to the change of land into residential areas according to research (Lin, 2021; Su & Qi, 2023; N. Zhang et al., 2022) that population development, built-up areas, and dense cities have spatial consistency with LST. Large-scale global urbanization has a significant impact, especially on the deterioration of regional thermal environments in urban agglomerations (Chen et al., 2020; N. Zhang et al., 2022). Urban agglomeration conditions also occur in areas with high urbanization in the Peri-Urban area of Surakarta City, which also tends to have high LST. The results of this research are in accordance with the results of various similar research topics where increasing urban activity causes an increase in surface temperature. Sustainable development planning for suburban areas, especially the Peri-Urban area of Surakarta City, is essential to form a sustainable city. In the context of periphery development, sustainability aims to make cities and settlements inclusive, safe, resilient, and sustainable in accordance with the SDGs program goal 11 (SDG11), namely building sustainable cities and communities (Jatayu et al., 2022). Regional planning is essential to overcome problems due to urbanization.

CONCLUSION

The Peri-Urban Area of Surakarta City is an area that has experienced urbanization due to the impact of the development of Surakarta City. Urbanization can drive an increase in LST. The results of the modeling using OLS and GWR show that urbanization with parameters of population, population density, percentage of built-up land, and urban form can explain LST. Increased urbanization on the outskirts of cities can significantly impact increasing land surface temperatures (LST). The growth of settlements, infrastructure, and intensive human activities causes land use changes, such as converting green land into buildings and roads. These changes reduce vegetation that functions as a natural heat sink and increase hard surfaces that absorb heat, ultimately resulting in increased land surface temperatures in suburban areas. The heat island effect is also common in rapid urban development on the outskirts of cities. High human activity, building materials that absorb heat, and lack of vegetation cause higher local temperatures than surrounding rural areas. To overcome this problem, sustainable measures are needed, such as increasing vegetation, smarter use of building materials, and urban planning that prioritizes temperature mitigation and reducing the heat island effect to create a healthier and more sustainable environment in the suburbs. Peri-urban planning is essential to control the impact of development from the city center so that urbanization not only causes problems but can be a momentum to build a sustainable city.

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