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STUDY OF URBAN HEAT ISLAND IN YOGYAKARTA CITY USING LOCAL CLIMATE ZONE APPROACH

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Abstract

Yogyakarta urban area has increased significantly for the past ten years and altered ecological features, such as inducing urban heat island (UHI). Our objectives are examining UHI characteristics in Yogyakarta urban with atmospheric variables which include air temperature and relative humidity and analyzing the UHI distribution using the LCZ method. This study uses the LCZ classification to spatially compare thermal characteristic and explain how land use and building geometry affect UHI. The system comprises 17 standard classes at the local scale, using quantitative approach which includes numerical data, such as aspect ratio, building heights, and street canyons to support the classification system. Three LCZ classes found in Yogyakarta urban *area are LCZ 3, LCZ 5, and LCZ 6. The LCZ variables which affect temperature and relative humidity are building heights, width of street canyons, and land use. The biggest thermal difference is ΔLCZ3-LCZ5 and ΔLCZ3-LCZ6, which happened during 08.00 – 12.00 and 16.00 – 20.00. Small UHI magnitude (< 2K) is affected by small difference in morphology and fabric. Medium UHI magnitude (2 – 5K) is mostly caused by large difference in fabric and small difference in morphology. In the future, the LCZ should be widely applied for urban planning regarding climatic mitigation.*

Keywords

Urban Heat Island, Local Climate Zone, Land Use, Building Height, Yogyakarta Urban Area

1. Introduction

Urban heat island (UHI) is an environmental issue in urban area. The effect of UHI results in the increasing temperature in urban landscape which is higher than its surrounding area (Sani, 1987). The intensity of UHI highly influenced by urbanization. As the population grows, the built-up area will continue to expand. According to (UN DESA, 2018), it is projected that 68% of the world's population will reside in urban area by 2050. Intensive urbanization results in the alteration of physical landscape and urban climate.

Urbanization changes our environment through some processes, such as physical, socio-cultural, demographic and economic change (Deppisch et al., 2015). Anthropological aspect regarding the alteration of natural landscape into urban land use pays significant tributes to atmospheric dynamics. For instance, built-up area made of concrete and cement is able to influence air temperature (Weng, 2001).

Urban land cover affects the input of thermal capacity. Artificial material has high rate on thermal capacity, thermal conductivity, and radiation consequently the material impacts on daylight heat absorbance and emit it in nighttime (Oke, 1982). As the urban heat storage increases, land surface temperature will rise accordantly, creating urban heat island (Oke et al., 1991).

Air temperature is the main variable used to measure the UHI. Stark contrast between urban and rural air temperature happens at nighttime reaching approximately 7 - 12°C, whereas at daytime the difference ranges from 1°C to 3°C (Stanganelli & Soravia, 2012). As the consequence of heat absorption at daytime and heat release at night, material surface emits thermal infrared at night which results in the temperature rise (Abdulrasheed et al., 2020; Ahrens, 2009).

In this study, we chose a rather homogenous terrain, characterized by morphological slope which ranges 0 – 2%. Yogyakarta is an ideal study field for the LCZ (local climate zone) approach due to its flat topography. Flat land accommodates UHI without disturbance of geographic barriers, resulting on almost non-existent vertical air flow. Therefore, every observing point only focusing on temperature and humidity without measuring air flow.

Yogyakarta urban area experienced a massive growth between the year of 2005 and 2015, with the percentage of 316.9% and 382.1% respectively, marked by a rapid urban sprawl in the suburbs (Marwasta, 2018). The expansion of built-up area in Yogyakarta provides a major landscape changes, such as the reduced open space and vegetation. Rapid urban sprawl in the suburbs influenced by the road network that linking the outer and inner city and the ownership of private vehicle (Marwasta, 2018). As the human activities thrive by the increase of built-up area and emissions, urban areas produce warmer temperature than the surrounding rural areas (Li et al., 2018; McDonnell & MacGregor-Fors, 2016).

In this paper, our specific objectives include: (1) examining UHI characteristics in Yogyakarta urban with atmospheric variables which include air temperature and relative humidity; (2) analyzing the UHI distribution using the LCZ method.

2. Literature Review

(Stewart & Oke, 2012) stated in their inventive paper that the zonation of climates is highly influenced by main variables as follows: land cover, land use, and building geometry. We adapted the LCZ method by using its main variables to help classification. The borderline distinction between this study and (Stewart & Oke, 2012) lies in the variables, hence we only applied aspect ratio among other geometric and surface cover properties. Aspect ratio being chosen to underline the significant impact of city morphology (Leconte et al., 2020).

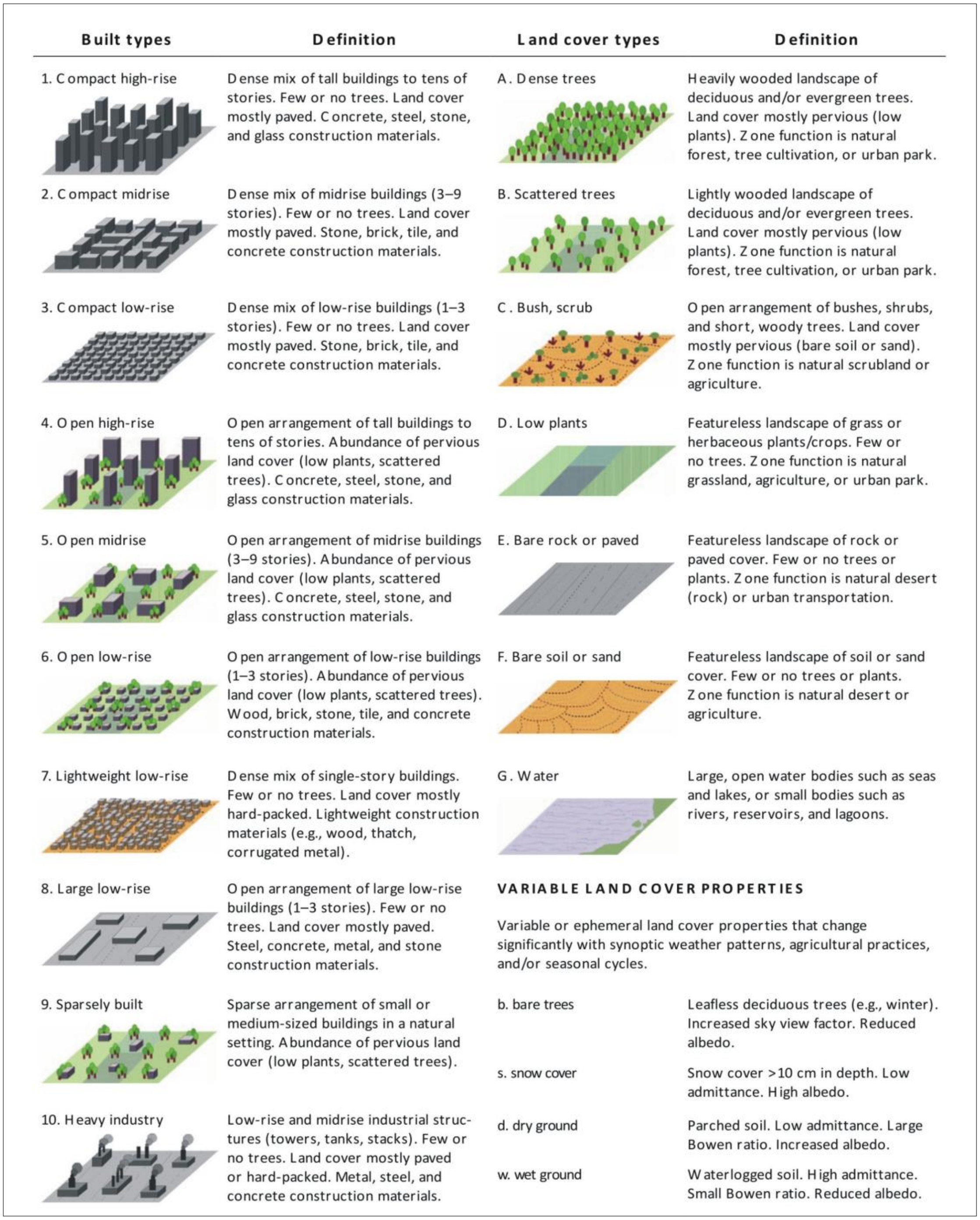
The local-scale zonation of LCZ performs an affordable research in a homogenous terrain like Yogyakarta. We easily examine the local climate in the flat landscape of Yogyakarta, characterized by slope of 0° to 2°, which represents an ideal study field for LCZ. Flat topography influences airflow and radiation in the city. On a majorly dominated gentle topography, airflow is reduced to minimal level due to the absence of geographic barriers such as mountainous area. Topography impact on airflow by generating mechanical and thermal aspects (Kokkonen et al., 2018). Mechanical aspect is topographic barrier deflecting ambient airflow, whereas thermal aspect refers to topographic influence by modifying diurnal surface energy balance and affecting thermal circulation. It is stated by (Stewart & Oke, 2012) the LCZ has the most ideal outcomes in a flat topography due to the minimal effect of airflow therefore UHI magnitude is maximum.

3. Methods

In order to examine data, we adopted the LCZ classification to spatially compare thermal characteristic and explain how UHI is affected by land use and building geometry. The LCZ method specifically uses classification based on land use/land cover. The system comprises 17 standard classes at the local scale, using quantitative approach which includes numerical data, such as aspect ratio, building heights, and street canyons to support the classification system. Hourly record of temperature and relative humidity are data collected to calculate UHI magnitude.

3.1. Local Climate Zone (LCZ):

The study areas are four points spread across within the boundary of Yogyakarta Urban Area. Those areas were deliberately chosen according to types of LCZ found in Yogyakarta. Through an interpretation using a land use map and Google Earth imagery, there are three LCZ classes in Yogyakarta which are LCZ 3, LCZ 5, and LCZ 6. Type of LCZ 3 was the most type we found, consequently we put two measurements in LCZ 3 located in the city center and suburban to collect hourly data. Four study areas were selected based on their meeting requirements of LCZ classification which include land use, average building height, and average width of street canyon.



Built types	Definition	Land cover types	Definition
1. Compact high-rise	Dense mix of tall buildings to tens of stories. Few or no trees. Land cover mostly paved. Concrete, steel, stone, and glass construction materials.	A. Dense trees	Heavily wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
2. Compact midrise	Dense mix of midrise buildings (3–9 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	B. Scattered trees	Lightly wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
3. Compact low-rise	Dense mix of low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	C. Bush, scrub	Open arrangement of bushes, shrubs, and short, woody trees. Land cover mostly pervious (bare soil or sand). Zone function is natural scrubland or agriculture.
4. Open high-rise	Open arrangement of tall buildings to tens of stories. Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	D. Low plants	Featureless landscape of grass or herbaceous plants/crops. Few or no trees. Zone function is natural grassland, agriculture, or urban park.
5. Open midrise	Open arrangement of midrise buildings (3–9 stories). Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	E. Bare rock or paved	Featureless landscape of rock or paved cover. Few or no trees or plants. Zone function is natural desert (rock) or urban transportation.
6. Open low-rise	Open arrangement of low-rise buildings (1–3 stories). Abundance of pervious land cover (low plants, scattered trees). Wood, brick, stone, tile, and concrete construction materials.	F. Bare soil or sand	Featureless landscape of soil or sand cover. Few or no trees or plants. Zone function is natural desert or agriculture.
7. Lightweight low-rise	Dense mix of single-story buildings. Few or no trees. Land cover mostly hard-packed. Lightweight construction materials (e.g., wood, thatch, corrugated metal).	G. Water	Large, open water bodies such as seas and lakes, or small bodies such as rivers, reservoirs, and lagoons.
8. Large low-rise	Open arrangement of large low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Steel, concrete, metal, and stone construction materials.	VARIABLE LAND COVER PROPERTIES	Variable or ephemeral land cover properties that change significantly with synoptic weather patterns, agricultural practices, and/or seasonal cycles.
9. Sparsely built	Sparse arrangement of small or medium-sized buildings in a natural setting. Abundance of pervious land cover (low plants, scattered trees).	b. bare trees	Leafless deciduous trees (e.g., winter). Increased sky view factor. Reduced albedo.
		s. snow cover	Snow cover >10 cm in depth. Low admittance. High albedo.
10. Heavy industry	Low-rise and midrise industrial structures (towers, tanks, stacks). Few or no trees. Land cover mostly paved or hard-packed. Metal, steel, and concrete construction materials.	d. dry ground	Parched soil. Low admittance. Large Bowen ratio. Increased albedo.
		w. wet ground	Waterlogged soil. High admittance. Small Bowen ratio. Reduced albedo.

Figure 1: *Definition of local climate zone (LCZ) classes*
(Source: Stewart & Oke, 2012)

As we can see in Figure 1, there are several classes of LCZ based on built-up areas and land covers. Built types consist of LCZ 1- LCZ 10, mainly using building geometry to differentiate every class. Land cover types refer to physical land types such as vegetation or water body. Land type uses font A – G for class symbols. This study categorizes LCZ using built types.

Mapping the LCZ classes requires delineation in the observation areas. The zonation formulates aspect ratio and building height to quantitatively determine the LCZ class. Delineation was conducted on a neighborhood scale characterized by similar geographic features such as slope, elevation, and wind direction. The LCZ classification system is determined using geometry variable which was narrowly chosen into building height and aspect ratio (H/W).

Borders for delineating local climate zones use various aspects such as width of the area, slope, land use, and geographic barrier, a natural landscape which segregates a region. Width of area varies from several hundred of meters to a few kilometers. In this study, the LCZ using neighborhood scale. The examined areas were limited by similar characteristics of slope and elevation to avoid any differences in thermal pattern (Stewart et al., 2014).

Physical boundaries which are building blocks circulated by secondary level road were used to determine circumferences of the examined local climate zone. According to Indonesian Law No 38 Year 2004 regarding roads, there are two systems of road networks, which include primary and secondary road network. Secondary road network is defined as a road connecting third secondary zone and lower-ranked zones within a region. Secondary zone functionally provides service sector for residents with local orientations and distributions. Third secondary zone consists of park, sports center, shopping center, community health center, city hall, mosque, parking lots, district office, police station, post office, civil center and recreations.

For the geometry aspect, we use aspect ratio and mean building height. Measuring building height requires building census in the study area which means we measured every single building in the area, referring to every building unit. The measured buildings had to meet basic functional qualifications as follows: having dimensional stability such as walls and a roof. We measured every building height in the LCZ zones using a distometer, an electronic device using laser technology for 3D measurement. Building height measurement was proceed using Excel to calculate the mean value. To calculate aspect ratio, we use formula:

$$\frac{H}{W} \quad (1)$$

with H: building height and W: width of the street.

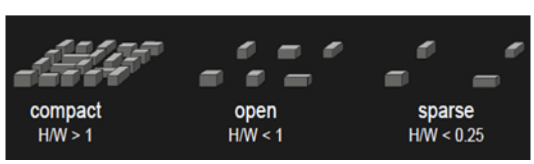


Figure 2: *Aspect ratio and its definition*

(Source: Stewart & Oke, 2012)

Aspect ratio and building height were chosen as the LCZ variables because built-up landscape acts as the main control of urban radiation, thus they will affect temperature and relative humidity.

3.2. UHI Analysis:

Examining the UHI to obtain data, we conducted a field observation to record hourly temperature and relative humidity for seven days in July 2019. July was chosen due to the minimal rainfall in Yogyakarta at the time. The measuring instruments we used were USB loggers placed in the height of 2 to 2.5 meters above the ground. Four loggers were strategically placed in four observing points based on the LCZ class.

Hourly temperature and relative humidity data were processed by using Excel to calculate daily mean value. The formula are as follows:

Daily mean temperature: $$\frac{Tmax+Tmin}{2} \quad (2)$$

Daily mean relative humidity: $$\frac{RHmax+RHmin}{2} \quad (3)$$

For the UHI magnitude, we use equation as follows:

$$\Delta T = LCZ_X - LCZ_Y \quad (4)$$

4. Results and Discussion

Land use in the study area is dominated by residential area. Building type is mostly low rise which spreads out evenly and creating a rather homogenous land cover. This landscape results in mini variants of LCZ 3, LCZ 5, and LCZ 6. The LCZ classes observed in Yogyakarta, all of which have area range from 10 – 22 hectare and length of 300 to 700 meter. Each observed LCZ class also has similar wind speed and direction. Similar wind direction is essential to create air flow and similar temperature across the study area which eventually results in a local climate zone.

4.1. Local Climate Zone:

According to the local climate zone classification by (Stewart & Oke, 2012), there are four types found in Yogyakarta urban area: LCZ 3, LCZ 5, and LCZ 6. Type LCZ 3 was found mostly in the inner part of the city and majorly distributed, thus we had two observation points to record LCZ 3 with cultural-tourism based land use (Tamansari) and commercial-region based land use (Malioboro). Type LCZ 5 and LCZ 6 were found in the outskirt of the city and suburban area.

Table 1: *Local Climate Zones in Yogyakarta Urban Area*

No	Study Area	Average height (H) (meter)	Average width (W) (meter)	Aspect ratio (H/W)	LCZ	Land Use
1	Gadjah Mada University (UGM)	12.71	15.05	0.84	Open midrise LCZ 5	Educational institution
2	Malioboro	9.21	3.79	2.43	Compact low rise LCZ 3	Commercial region, tourism
3	Tamansari	5.61	1.17	4.82	Compact low rise LCZ 3	Residential area, tourism
4	Banyuraden	6.16	6.26	0.98	Open low rise LCZ 6	Residential area, paddy field

(Source: Authors' Own Observation)

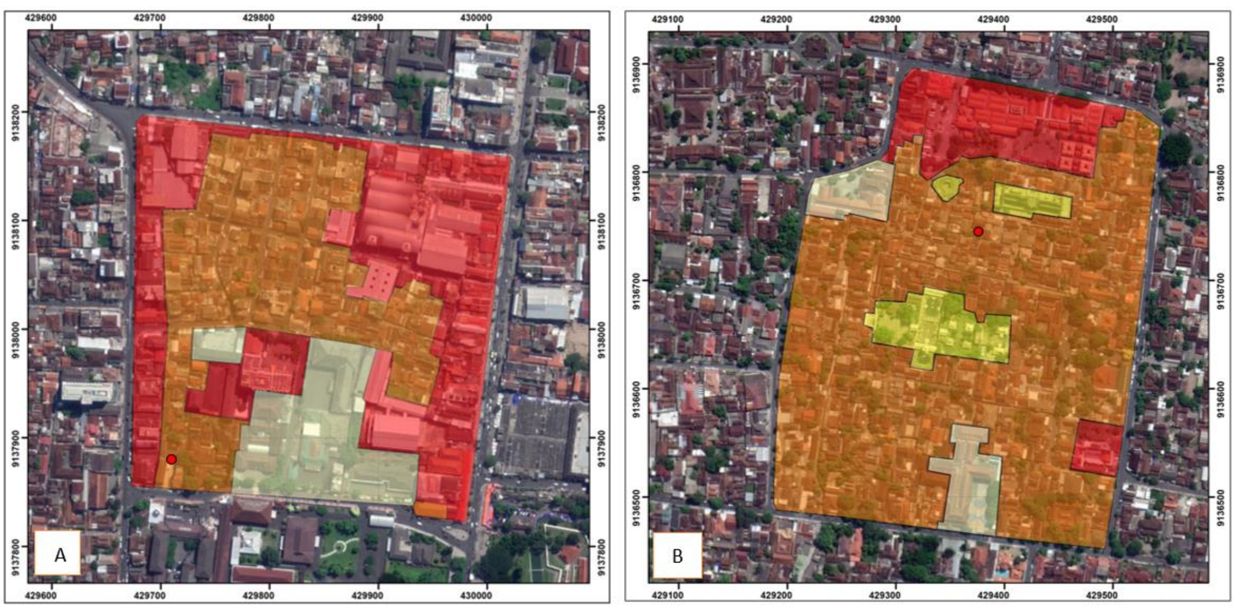


Figure 3: *Land Use Map Of LCZ 3 Malioboro (A) And Tamansari (B) In 2019, Red Colored Area: Commercial Region; Orange Colored Area: Residential Are; Light Pink Colored Area: School; Yellow Colored Area: Tourism Area;, Red Dots: Thermal Logger*

(Source: Authors' Own Illustration)

LCZ 3 consists of compactly dense low-level building. The average building height in Malioboro is 9.21 m while Tamansari is 5.61 meter. Both is characterized by densely compacted buildings and dominated by residential area.

LCZ 5 is characterized by tall building with average value of 15.05 m. There are adequate open spaces in the LCZ 5 to create an open landscape without densely compacted buildings. Furthermore, the landscape in the LCZ 5 (UGM campus) has a very wide street canyon with aspect ratio value at 0.84. The LCZ 6 in Banyuraden is almost similar in terms of mean building height compared to Tamansari. the significant aspect that differentiates between those two is the value of aspect ratio. LCZ 6 has much lower aspect ratio than LCZ 3 because the landscape is widely separated by open space.

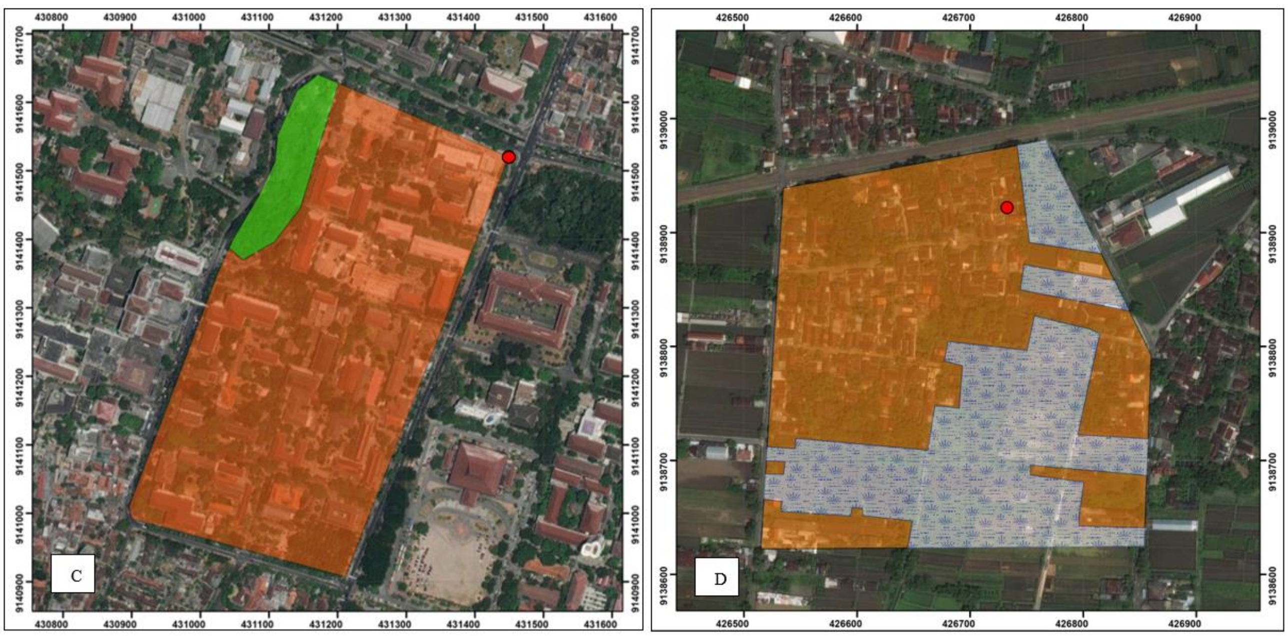


Figure 4: *Land Use Map Of LCZ 5 (C) And LCZ 6 (D) In 2019, Orange Colored Area (C): Campus Area; Orange Colored Area (D): Residential Area, Green Colored Area: Campus Forest Park, Striped Blue Area: Irrigated Paddy Field, Red Dots: Thermal Logger*

(Source: Authors' Own Illustration)

4.2. UHI Characteristics in Yogyakarta Urban Area:

Observing UHI magnitudes used two variables which are air temperature and relative humidity. Both variables were further calculated to obtain daily mean value.

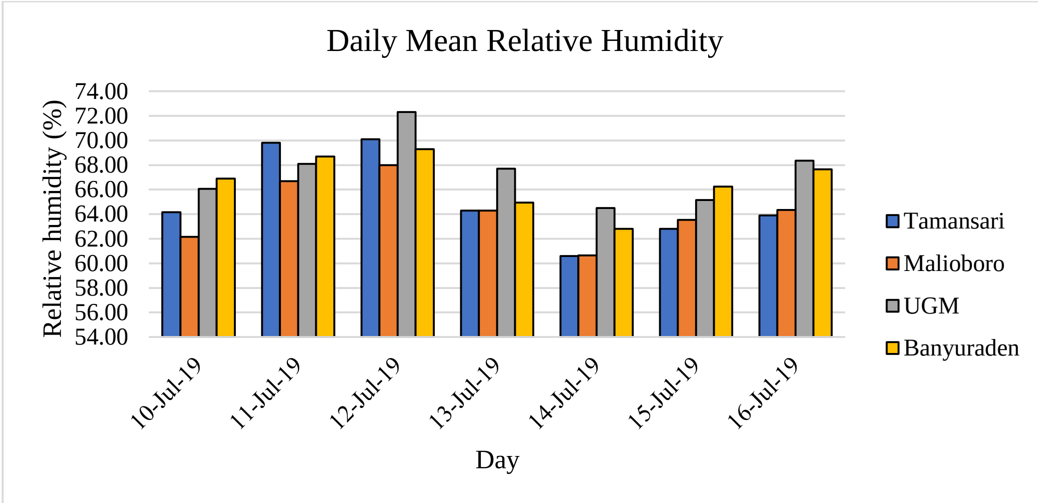


Figure 5: *Daily Mean Relative Humidity in The Study Areas*

(Source: Authors' Own Illustration)

Daily mean relative humidity shows increasing trend in the study areas during the first three-day of observation before plummeting on July 13th and 14th. It then slowly increased for the last couple of observation days. Overall, UGM area displays high relative humidity throughout the whole week, followed closely by Banyuraden. Meanwhile, Malioboro had a five-day streak of being the lowest relative humidity on the first three days of observation before it upstaged Tamansari by a close gap on the 15th and 16th. Relative humidity set the highest record on July 12th and the lowest record on July 14th where all observation points plummeted, then gradually increased again on the last couple of days of observation.

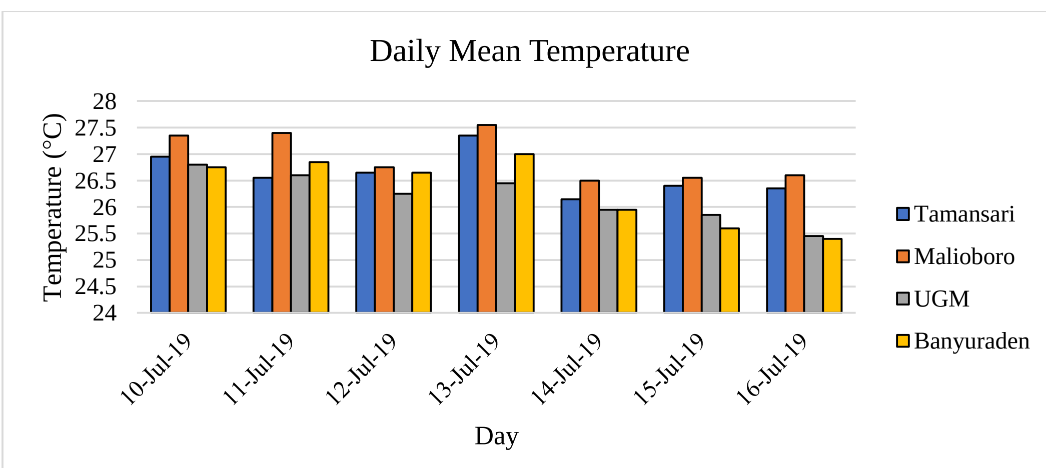


Figure 6: *Daily Mean Temperature in The Study Areas*

(Source: Authors' Own Illustration)

In all of the record days, Malioboro always led, followed closely by Tamansari and occasionally by Banyuraden. Tamansari set the second highest daily mean temperature on 10 July and 13 – 16 July. However, it is noteworthy that Tamansari was the lowest compared to the other areas on 11 July. Banyuraden had a variative trend throughout the week, which was increasing in the first four days before plummeting on 14 July and became the lowest daily mean temperature on 14 – 16 July. The campus area of UGM had a constant decreasing trend for the first three days before spiking on 13 July and continued to decrease again for the rest of the week.

Looking first of all at the study areas, they undergo serious drop on both temperature and relative humidity on 14 July. From there, relative humidity in the study areas gradually increased throughout the week with a high of above 68% (recorded in UGM Campus), while Tamansari bottomed out at 62.8%. However, temperatures in both of UGM and Banyuraden kept decreasing for the rest of the week whereas Malioboro slowly rise again and Tamansari slightly fluctuated. The humidity dropped on 14 July did not result on increasing temperatures in all of the study areas which slightly diverted the dynamic of temperature-humidity.

Relative humidity is defined as a measure of the actual amount of water vapor contained in the air compared to the total amount of water vapor that can be contained in the same temperature (Ahrens, 2009). Warm air can possess more water vapor (moisture) than cold air, so with the same amount of absolute/specific humidity, air will have a higher relative humidity if the air is cooler, and a lower relative humidity if the air is warmer. What we feel outside is the actual amount of moisture (absolute humidity) in the air.

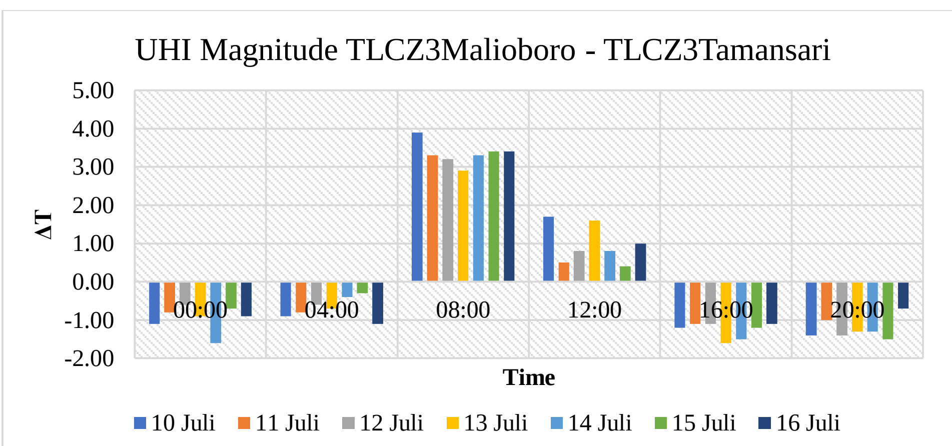


Figure 7: *The UHI Magnitude Between LCZ 3*

(Source: Authors' Own Illustration)

Heat island magnitude is used to express temperature differences between selected LCZ classes. Despite being assigned in the same class, Malioboro and Tamansari showed significant difference regarding temperature. Malioboro displayed higher temperature on morning and noon which later dropped on the late afternoon. Land use of Malioboro serves as commercial region whereas Tamansari is a major residential area and cultural tourism. Nevertheless, both characterized by similar building pattern, such as mean height and building materials, which makes up similar aspect ratio. The highest thermal difference was obtained at daytime around eight o'clock in the morning with the high magnitude of 3.9°C (10 July 2019). Heat island magnitude in the morning and evening were thoroughly constant for seven days. Meanwhile, magnitude at midafternoon fluctuated sharply from day to day although it was still higher in Malioboro compared to temperature in Tamansari. It is noteworthy that warming process in Malioboro was more rapid than Tamansari. Material of the buildings in Malioboro is considered to influence the heat release by emitting infrared radiation thus increasing surrounding temperature (Ahrens, 2009).

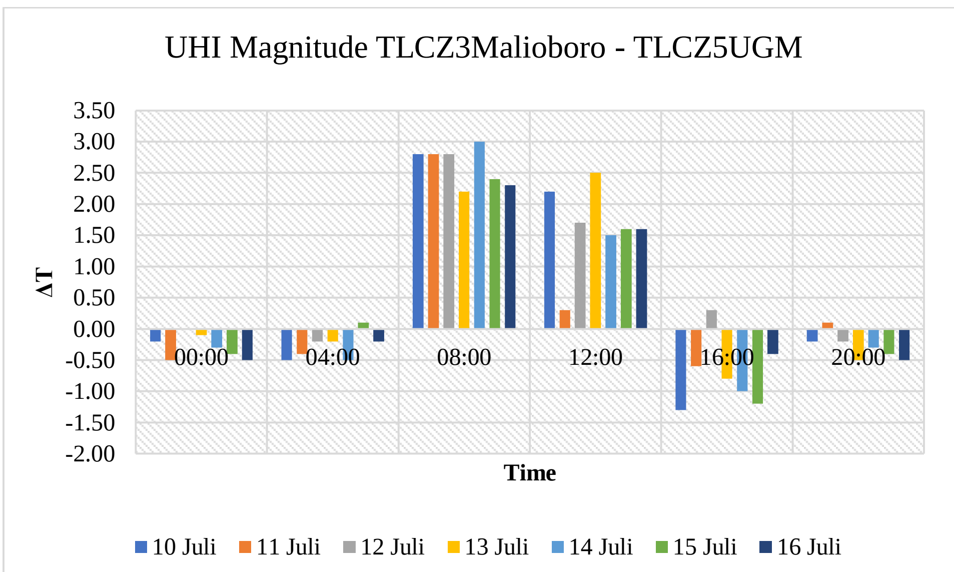


Figure 8: *The UHI Magnitude Between LCZ 3 And LCZ 5*

(Source: Authors' Own Illustration)

LCZ 3 Malioboro also had higher temperature than LCZ 5 UGM, especially in the daytime, however it drastically lowered in the evening and nighttime. At night, the magnitude graph displayed negative values as a result of higher nighttime temperature in UGM. Meanwhile, Malioboro experiencing rapid temperature drop at night, hence the negative trend shown in the graphic. Many buildings in Malioboro dominated by light gray colored roofs which possibly could enhance the albedo and lower heat storage (Ahrens, 2009). Compact building in Malioboro also has a narrow street canyon with high aspect ratio to provide more shades from the sun. Nighttime cooling in Malioboro is faster than other observing points due to lower out going radiation.

Higher daily mean relative humidity in UGM compared to Malioboro was affected by a contrast in regarding land use. The study area in UGM has an open rise area with tall buildings which surrounded by a green open space. The buildings in UGM have also been supported by green architectural such as cool pavements and cool/green roof. The UGM campus area has a quite amount of open area to allow evapotranspiration. Land surface and vegetation receive solar radiation and release water vapor into the air. The phase change of liquid into gas requires heat from the surrounding environment which results on the decreasing of air temperature, therefore evaporation is a cooling process (Ahrens, 2009). Latent heat used in the evaporation process requires high level of humidity which is provided in the UGM campus area by the abundant green space. High humidity in the sunny tropics results on high latent heat flux (Wang et al., 2019). Latent heat or hidden warmth was one of the key factors affecting the UHI magnitude at night between LCZ 5 (UGM) and LCZ 3 (Tamansari).

The lack of open space in Malioboro reduces water vapor required for transpiration. The LCZ 3 in Malioboro is dominated by built-up area and impervious surface with high rate of anthropogenic metabolism which leads to air pollution, surface runoff, and the diminishing rate of evaporation. Surface impermeability influences heat dynamic in Malioboro. The reduced rate of evaporations also impacts on latent heat flux.

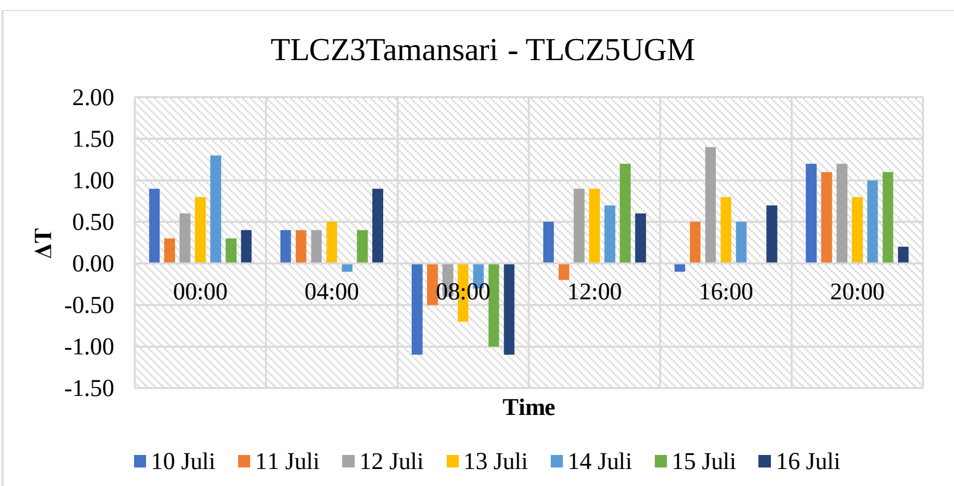


Figure 9: *The UHI Magnitude Between LCZ 3 (Tamansari) And LCZ 5 (UGM)*

(Source: Authors' Own Illustration)

LCZ 5 in UGM had the lowest daily mean temperature trend compared to other claasses. Moreover, the area had the highest humidity at 72.3%. the campus area has ideal open space area which provides impervious surface and becomes natural control for temperature and humidity (Oke, 1988).

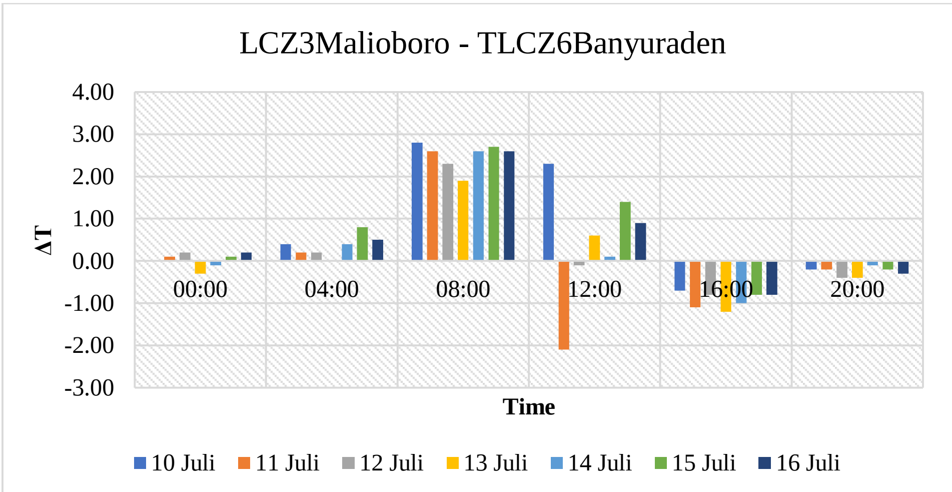


Figure 10: *The UHI Magnitude Between LCZ 3 (Malioboro) And LCZ 6 (Banyuraden)*

(Source: Authors' Own Illustration)

The UHI magnitude between LCZ 3 (Malioboro) and LCZ 6 (Banyuraden) significantly happened during eight in the morning until 16.00 in the afternoon.

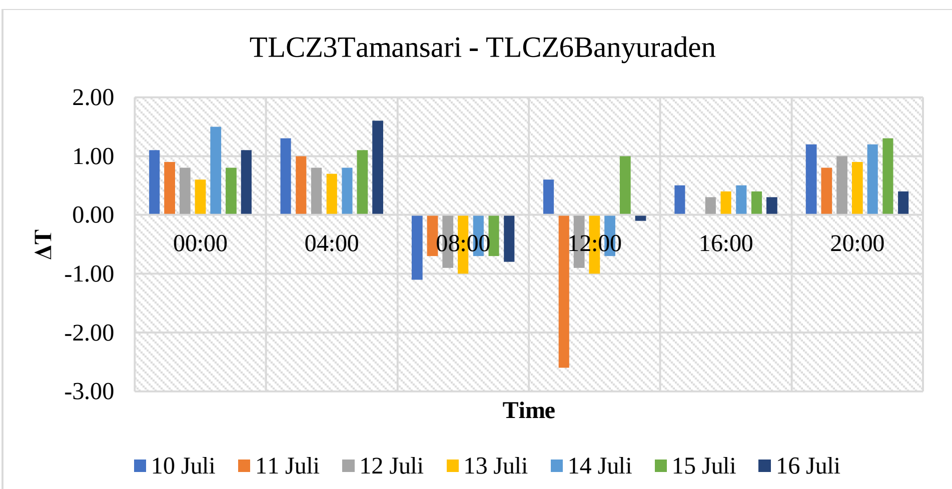


Figure 11: *The UHI Magnitude Between LCZ 3 (Tamansari) And LCZ 6 (Banyuraden)*

(Source: Authors' Own Illustration)

Tamansari and Banyuraden had a range of UHI magnitude between 0.1 – 2.6 with average of 0.86.

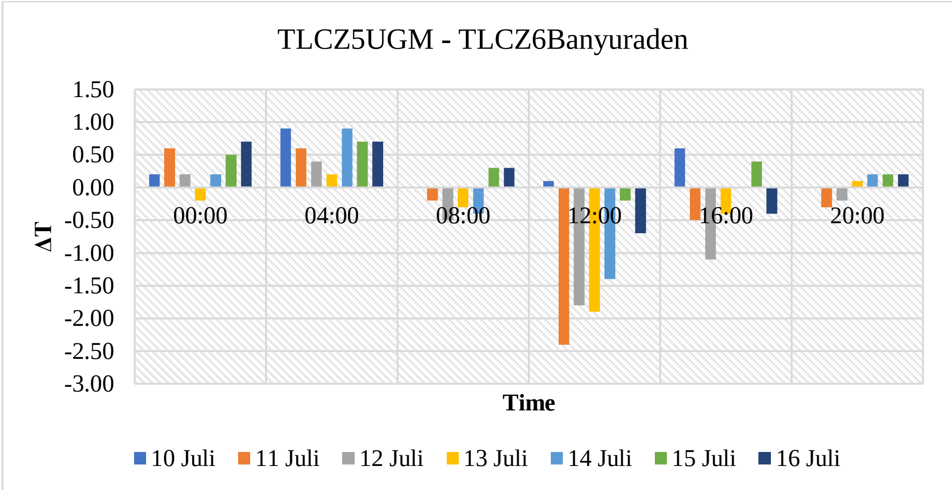


Figure 12: *The UHI Magnitude Between LCZ 5 (UGM) And LCZ 6 (Banyuraden)*

(Source: Authors' Own Illustration)

Heat island magnitudes throughout the study areas have a low magnitude that lower than 2K and medium (2 – 5 K). Low magnitude is found in the calculation between LCZ 3 (Tamansari) and LCZ 6 (Banyuraden). Medium magnitude is recorded in the thermal differential between LCZ 3 (Malioboro) and LCZ 5 (UGM Campus). Low magnitude happens due to high similarity of morphology and materials, while medium magnitude is affected by large difference in building fabric however both have similarity regarding morphology (Stewart, 2011). Morphology includes variables such as building height and surface roughness as the combination of aspect ratio. Fabric includes the physical features such as albedo, permeability, and thermal admittance.

4. Conclusion

The LCZ approach to study UHI characteristics used variables that include aspect ratio, building height, and land use. LCZ 3 Malioboro and Tamansari is a compact low rise with low building height and a densely compacted area. LCZ 5 is an open green space area surrounded by tall building above 12 meters. LCZ 6 is characterized by low building area with adequate open space. A change in air humidity is affected by a change in temperature. Variables working to influence humidity including building geometry, materials, street canyon, land use, and green open space. Heat island magnitudes found in the study areas are low magnitude and medium magnitude. Low magnitude has lower value than 2 K, whereas medium ranges between 2 – 5 K. medium magnitude is obtained from the calculation between LCZ 3 and LCZ 5, LCZ 6. Medium type is affected by large difference in fabric and similarity in morphology. Type low magnitude found between LCZ 5 and LCZ 6, which influenced by similarity in fabric/materials of the buildings and morphology.

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