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Research Paper

Threat and Vulnerability of Thermal Discomfort in Yogyakarta City

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Abstract

The world's attention to climate issues is increasing as the issue of global warming and climate change emerges. Several studies with the scope of cities and urban areas concluded that urban surface temperatures have an increasing trend. This phenomenon will have an impact on the thermal comfort of urban population. Yogyakarta City as one of the National Activity Centers (PKN), is experiencing rapid urban development and leads to become a metropolitan city so it needs to be studied regarding its thermal comfort. This research is intended to identify the potential and vulnerability of thermal discomfort in Yogyakarta City. The identification of potential discomfort is carried out using the Discomfort Index (DI) approach and the Land Surface Temperature (LST) value. Meanwhile, vulnerability is identified in the social aspects of population. Furthermore, the potential and vulnerability scores are assessed to get an overview of thermal discomfort mitigation priorities. Based on DI analysis, thermal discomfort is felt by more than 50% of the Yogyakarta's residents and it is estimated that in the future will get worse. By looking at the distribution of LST values, the high potential for discomfort is in the city center and has expanded to the north and northeast. Meanwhile, areas with high vulnerability are located in the center and south side of Yogyakarta City. From the combined assessment of threat and vulnerability, the areas that are the top priority for mitigation are in the center of Yogyakarta City, which include 7 districts, namely Danurejan, Gedongtengen, Gondomanan, Jetis, Kraton, Ngampilan, and Pakualaman. The medium priority districts are Gondokusuman and Wirobrajan.

Keywords

Thermal Discomfort, Potential, Vulnerability, Mitigation

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1. INTRODUCTION

The world's attention to climate issues has increased in at least the last five decades as the issue of global warming and climate change has emerged. Since 1970, there has been much documentation of global atmospheric temperature measurements along with the rapid increase in surface temperatures. From that year to 2017, there are indications that global temperatures have increased by 0.9°C. Another source states that compared to the 1850-1900 period, global surface temperature increased by 0.99°C at the beginning of the 21st century. The increase occurred in both land and oceans although the average temperature increase did not occur constantly and was not spatially uniform. Compared to the oceans, the temperature increase on land was greater (1.59°C) than in the oceans at 0.88°C (Rohr et al., 2018; Pörtner et al., 2022).

Regionally, cities are generally warmer than adjacent rural areas due to the rapid urbanization process in recent decades. Intensive urbanization represents rapid infrastructure development, urban sprawl, and high urban activity, which can lead to a decrease in green space (Guo et al., 2016; Putri et al., 2021). On the other hand, air temperature has a high sensitivity to urban morphology and urban canopies. Built-up land that dominates urban areas retains heat for longer, causing temperatures to be warmer than the surrounding areas. This phenomenon of higher urban surface and atmospheric temperatures compared to surrounding areas is called Urban Heat Island (UHI) (Kantzioura et al., 2012; Maggiotto et al., 2014). Much research has been done on climate, including urban climate. However, it is still unclear how global warming affects UHI and the relationship between the two (Alcoforado and Andrade, 2008; Ginzburg and Alexandrov, 2020). However, climate change and continued warming are expected to exacerbate the UHI situation albeit to varying degrees depending on geographic location as well as land use and land cover changes (Thanvisitthpon et al., 2018; Wolf and McGregor, 2013). On the other hand, UHI has little effect on global average temperature because urban areas comprise only 1% of the Earth's surface area, but at the local or national scale, more warming occurs because of urbanization (Kachenchart et al., 2021; Wang and Yan, 2016). Several studies with the scope of cities and urban areas concluded that urban surface temperatures have an increasing trend. Dewan et al. (2021) in his research on five major cities in Bangladesh concluded that there are 4 cities that have a positive trend over a period of 20 years (2000-2019) in the observation of daytime Surface Urban Heat Island Intensity (SUHII). Meanwhile, 1 city was recorded to have a negative trend in night time observations. Based on long term study (2002-2018), more than half of cities in mainland China experienced a significant increase in canopy layer urban heat island (CLUHI) and surface urban heat island (SUHI) (Yao et al., 2021). In Lahore City, Pakistan, the average temperature trend from 1950-2017 shows an increase. Although from 1951-1997 the increase was less, after 1999 the increase was faster, especially in urban areas (Abbas et al., 2018).

Air temperatures that continue to increase cause thermal discomfort, especially for residents living in urban areas. However, thermal comfort cannot be separated from the ability to adapt to environmental conditions and climatic zones (Putri et al., 2021). Individual factors that may influence adaptive capacity and the ability to cope with extreme temperatures include demographic factors (age, gender, family status), health status (pre-existing diseases), access to resources, support and information related to heat protection measures, and mobility. These factors determine sensitivity to heat and form the basis of the heat vulnerability index (Wolf and McGregor, 2013).

Urban heat vulnerability will be higher for certain groups of people, namely the elderly, minority groups, people who are linguistically and socially isolated, low-income groups, and those with pre-existing medical conditions (Monaghan et al., 2014). In his research, Ahmadalipour et al. (2019) estimated that the risk of death for people over 65 years old in the Middle East and North Africa (MENA) will increase by 8-20 times in the last 30 years of the 21^{st} century if no climate change mitigation planning is done. However, if global warming is kept to 2°C, the mortality risk is expected to increase only 3 - 7 times over the same period. Meanwhile, Ebi et al. (2021) noted that heat-related mortality has declined considerably in industrialized countries in recent decades. However, how sustainable the decline or the opposite condition is depends on the implementation of effective adaptation strategies.

Adaptation strategies are inseparable from the implemented mitigation efforts. Mitigation is intended to reduce the risk of a threat or danger. In an effort to improve the management of heat-related health risks, spatialized heat vulnerability informations are needed. With this information, decision makers have a basis for consideration in allocating resources to mitigate extreme heat events (Wolf and McGregor, 2013). Current research on the impacts of climate change to human mainly includes on spatial layout and population distribution; human health; and human thermal perception of urban temperature (Zhang et al., 2022).

In their publication, Zhou et al. (2022) mapped the characteristics and trends of research on urban microclimate. Urban microclimate research experienced a rapid increase starting from 2005. ”Thermal comfort” is a keyword that has the highest frequency in the 1998-2005 period and continues until the 2006-2015 period with a more specific keyword, namely ”outdoor thermal comfort”. Meanwhile, Zhang et al. (2022) said that currently research on human climate comfort is being carried out with the aim of solving especially the aspects of tourism and its development as well as the residential environment.

Spatially, research publications on urban microclimate (thermal comfort and thermal discomfort can be included in it), recorded the most in China and the United States. In Indonesia as a country that has variations in geographical physical conditions, culture, language, and food, research on thermal comfort is still limited. However, research of this theme has been conducted by Wati (2017) with the aim of daily comfort levels in DKI Jakarta and trends in comfort levels from year to year using the THI comfort index. The results showed that during the 1985-2012 period there was an increasing trend in the THI index with a significance of >50%, indicating that the level of comfort in DKI Jakarta tended to be increasingly uncomfortable. The percentage of discomfort is getting bigger towards the center of the city. In Bandar Lampung, the Discomfort Index has been studied by Siami and Ramadhani (2019). Based on secondary data on weather parameters of Teluk Betung Station in 2007-2017, it is known that in the Discomfort Index analysis, Bandar Lampung City faces varying conditions. At high temperatures and humidity, most residents feel severe stress. At average temperature and humidity, more than 50% of people feel uncomfortable. At low temperatures and humidity the population did not feel any discomfort. However, every year Bandar Lampung City has shown unpleasant conditions, especially at high temperatures and average temperatures. Setiawati et al. (2021) examine heat vulnerability in Medan City using Heat Vulnerability Idex (HVI) based on commonly used health indicators and principal component analysis (PCA). The results showed that the impact of heat stress is at an alarming level and the heat risk map has not been included in the spatial master plan for consideration.

Yogyakarta City as one of the National Activity Centers (PKN), is experiencing rapid urban development and is leading to become a metropolitan city (Marwasta, 2018), so it needs to be studied regarding its thermal comfort. Related research that has been carried out so far has focused more on descriptions of conditions and classification of comfort/discomfort itself using the Discomfort Index (DI), Thermal Humidity Index (THI) approach, as well as public perception. The development of the study carried out was more on exploration and explanation regarding factors that influence thermal comfort. Nurmaya et al. (2022) had conducted research with the aim of knowing thermal comfort using the Discomfort Index (DI) method based on secondary data from the Gamping Climatology Station in 2004-2020 and Mlati Climatology Station in 2017-2020. The analysis results show a value of 24.97°C which shows that more than half of the residents of Yogyakarta City feel uncomfortable which can cause heat stress. Meanwhile, Marwasta and Nurhidayat (2019) had conducted research on the influence of urban physical development on housing comfort using a combination method between remote sensing image interpretation, field surveys, and interviews. The results show that most residents of Yogyakarta City actually perceive that environmental comfort over the past 10 years has remained relatively unchanged. In contrast, the perception of residents who live in Sleman and Bantul regencies as suburban areas mostly feel that the environment is getting worse. This is inseparable from the phenomenon of the declining intensity of development in the city center due to limited land while the suburban areas have begun to experience building densification. On a more specific theme, Nucifera et al. (2022) conducted research with the aim of identifying the level of tourist comfort based on climatic parameters through field measurements and detailed area mapping at several tourist village locations. The results show that each tourist village location is in uncomfortable temperature conditions and most are in comfortable conditions for humidity parameters. In this research, thermal discomfort is studied in the context of mitigation, by identifying the threat and vulnerability of discomfort to obtain an overview of risks and mitigation of a disaster. Identification of potential discomfort is carried out using the Discomfort Index (DI) approach and Land Surface Temperature (LST) values. Meanwhile, vulnerabilities were identified in the social and population aspects. The results of potential and vulnerability identification are further assessed to obtain an overview of spatial priorities for mitigating thermal discomfort. The spatial priority in question is shown in district units.

2. EXPERIMENTAL SECTION

2.1 Study Area

Yogyakarta City is part of and the capital of the Special Region of Yogyakarta (DIY). Relatively, Yogyakarta City is located in the center of Yogyakarta, while absolutely it is located at 110°24’19”-110°28’53” East Longitude and between 07°15’24” - 07°49’26” South Latitude. With an area of 3,280 hectares, Yogyakarta City is divided into 14 districts, 45 sub-districts, 616 community associations (RW) and 2,532 neighborhood associations (RT). In this study, the unit of analysis is at the district level.

2.2 Data Requirements and Analysis

In this study, a description of the potential for thermal discomfort was carried out through the analysis of Discomfort Index (DI) and Land Surface Temperature (LST). For DI analysis, temperature and relative humidity data are required. The temperature and relative humidity data used are air temperature data at an altitude of 2 m and monthly relative air humidity from 1990-2020 derived from ERA 5 data. Here is the Equation (1) used to calculate DI (Thom, 1959).

$$\mathrm{DI} = T - 0.55(1 - 0.01RH)(T - 14.5) \tag{1}$$

where DI is Discomfort Index (°C), T is temperature (°C), and RH is relative humidity (%). The classification of DI values obtained is presented in Table 1.

Table 1. Description, Classes and Ranges of Thom’s Discomfort Index

Description	Range (°C)
No discomfort	< 21
Under 50% of the population feels discomfort	21-23.99
Over 50% of the population feels discomfort	24-26.99
Most of the population feels discomfort	27-28.99
Everyone feels discomfort	29-31.99
State of medical emergency	32

Meanwhile, the LST value comes from processing Landsat 8 satellite image data in 2020 in bands 4, 5, 10, and 11 using ArcGIS software based on the following calculation Equation (2) (Rajeshwari and Mani, 2014).

$$L_\lambda = M_L Q_{cal} + A_L \tag{2}$$

where L_λ is TOA spectral radiance (Watts/(m^2 × srad × μm)), $\mathrm{M_L}$ = Band-specific multiplicative rescaling factor from the metadata ($\mathrm{M_L}$ BAND4 = 0.010332; $\mathrm{M_L}$ $\mathrm{BAND_5}$ = 0.0063228; $\mathrm{M_L}$ $\mathrm{BAND_{10}}$ = 0.0003342;and $\mathrm{M_L}$ $\mathrm{BAND_{11}}$ = 0.0003342), $\mathrm{Q_{cal}}$ is Band-specific additive rescaling factor from the metadata, $\mathrm{A_L}$ is Band-specific additive rescaling factor from the metadata ($\mathrm{A_L}$ $\mathrm{BAND_4}$=-51.66122; $\mathrm{BAND_5}$ = -31.61409; $\mathrm{A_L}$ $\mathrm{BAND_{10}}$ = 0.1000; $\mathrm{A_L}$ $\mathrm{BAND_{11}}$ = 0.10000). From Equation (2), the Brightness Temperature Value is then calculated with the Equation (3).

$$TB = \frac{K_2}{ln(\frac{K_1}{L_\lambda}) + 1} \tag{3}$$

where TB is Brightness temperature (K), $\mathrm{K_1}$ is Band-specific thermal conversion constant from the metadata, and $\mathrm{K_2}$ is Band-specific thermal conversion constant from the metadata ($\mathrm{K_1}$ $\mathrm{BAND_{10}}$ = 774.89; $\mathrm{K_1}$ $\mathrm{BAND_{11}}$ = 480.89; $\mathrm{K_2}$ $\mathrm{BAND_{10}}$ = 1,321.08, and $\mathrm{K_2}$ $\mathrm{BAND_{10}}$ = 1,201.14). The next step from the results of Equation (3) is to calculate the Normalized Difference Vegetation Index with the Equation (4).

$$NDVI = \frac{BAND_5 - BAND_4}{BAND_5 + BAND_4} \tag{4}$$

where NDVI is Normalized Difference Vegetation Index, $BAND_5$ is reflection in the near-infrared spectrum of Landsat 8, and $BAND_4$ is reflection in the red range of the spectrum of Landsat 8. From Equation (4), Fractional Vegetation Cover is then calculated using the Equation (5).

$$FVC = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}} \tag{5}$$

where FVC is Fractional Vegetation Cover, $NDVI_{soil}$ is NDVI value of soil = 0.2 and $NDVI_{veg}$ is NDVI value of vegetation = maximum value of NDVI. The next step is Land Surface Emissivity through the following Equation (6).

$$LSE = \varepsilon_s \times (1 - FVC) + \varepsilon_v \times (FVC) \tag{6}$$

where LSE is Land Surface Emissivity, ε is emissivity of soil and vegetation (ε_s $BAND_{10} = 0.971$; ε_s $BAND_{11} = 0.977$; ε_v $BAND_{10} = 0.987$, and ε_v $BAND_{11} = 0.989$). From steps (2) to (6), the Land Surface Temperature value is obtained through Equation (7). The higher the LST value, the higher the potential discomfort. To describe the level of potential discomfort, the LST value is categorized into three classes and given a score of 3 for high potential, score 2 for medium, and score 1 for low.

$$\begin{aligned} LST = & TB_{10} + C_1(TB_{10} - TB_{11}) + C_2(TB_{10} - \\ & TB_{11})^2 + C_0 + (C_3 + C_4 W)(1 - \varepsilon)(C_5 + \\ & C_6 W)\Delta\varepsilon \end{aligned} \tag{7}$$

where LST is Land Surface Temperature, TB_{10} and TB_{11} is Brightness temperature of BAND 10 and BAND 11, and C is Split Window Coefficient (C_0 = - 0.268; C_1 = 1.378; C_2 = 0.183; C_3= 54.300; C_4= - 2.238; C_5 = - 129.200; C_6 = 16.400).

Vulnerability to thermal discomfort is identified in the social aspects of population. The social aspects in question include the availability of health facilities (number of hospitals, clinics, health centers, and pharmacies), population density, and the percentage of the elderly population. For population density, it is obtained from the ratio of the total population to the total area of each district. Meanwhile, the percentage of the elderly population is obtained from the ratio of the population aged 65 years and over to the total population. The data used for the three variables is secondary data derived from the Central Bureau of Statistics publication. Each variable and total vulnerability is categorized into 3 classes and scored in the same way as the scoring of potential inconvenience. Meanwhile, the description of mitigation priorities is obtained from the risk calculation equation approach, namely the multiplication of the potential class score with vulnerability. From the calculation results, it is categorized into 3 priority classes, namely high priority, medium priority, and low priority.

3. RESULT AND DISCUSSION

3.1 Thermal Discomfort Threat

The calculation results show that the average monthly DI of Yogyakarta City is 24.26°C. As presented in Figure 1, the pattern formed is that DI increases in the January-April range, decreases in May-August, and rises again in September-December. April is the period where the DI value is the highest (25.07°C). Meanwhile, the lowest DI value occurs in August (22.85°C), indicating that most residents feel optimal comfort in August. This pattern is in line with the research Nurmaya et al. (2022) which also identified DI values to describe heat stress in Yogyakarta City using air temperature and relative humidity data for the 2004-2020 period.

Based on the classification of DI by Thom (1959), the average number obtained indicates that more than 50% of the population feels discomfort. The same thing has been stated in research Nurmaya et al. (2022) with an average index of 24.97°C which can cause heat stress. In fact, using the Temperature Humidity Index (THI) approach, Marwasta and Nurhidayat (2019) said that of the 30 sampling points in Yogyakarta City, 29 points were classified into the very uncomfortable category and 1 point was not comfortable.

In the future, it is estimated that there will be more people who feel thermal discomfort at a higher level. This is based on the trend of DI calculation results in the last 30 years (1990-2020). In Figure 2, it can be seen that the DI value forms a graph that continues to increase. During this period, the lowest DI occurred in 1991 and the highest DI occurred in 2016. The potential for increasingly uncomfortable temperatures in Yogyakarta City is inseparable from the function and physical development of Yogyakarta City. Urban expansion and land cover change, urbanization, and human activities are the main influences on urban climate. Massive urban development leaves small spaces of green open areas so that the city becomes warmer (Karyono, 2018). However, because the city's core land has been limited, it is possible that in the future within a certain period of time the dynamics of environmental temperature in the city center will be relatively stable due to the decline in the number of buildings and instead the dynamics in the form of an increase in environmental temperature will be more pronounced in the suburban area due to the expansion of built-up land. This phenomenon has been conveyed by Marwasta and Nurhidayat (2019) in their research on the influence of urban physical development on housing comfort.

As one of the potential variables for further thermal discomfort, the results of the Landsat Image analysis show that the average LST of Yogyakarta City is 32.15°C with a minimum value of 27.55°C and a maximum value of 37.53°C. The average LST value taken at the scope of the district area is in the range of 3.30°C to 33.26°C. Meanwhile, the results of the analysis (Atianta, 2020) using Landsat 8 imagery in June 2018 shows that the LST of Yogyakarta Urban Area

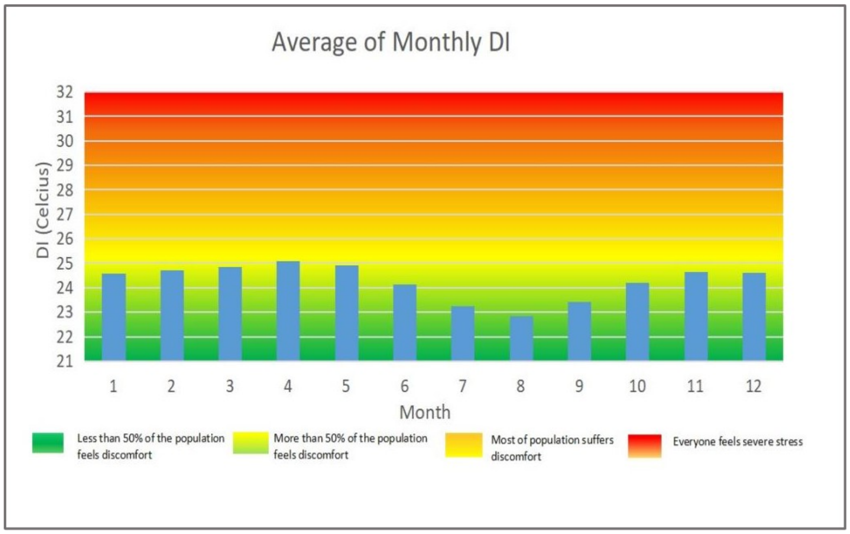

Figure 1. Average of Monthly Discomfort Index in Yogyakarta City

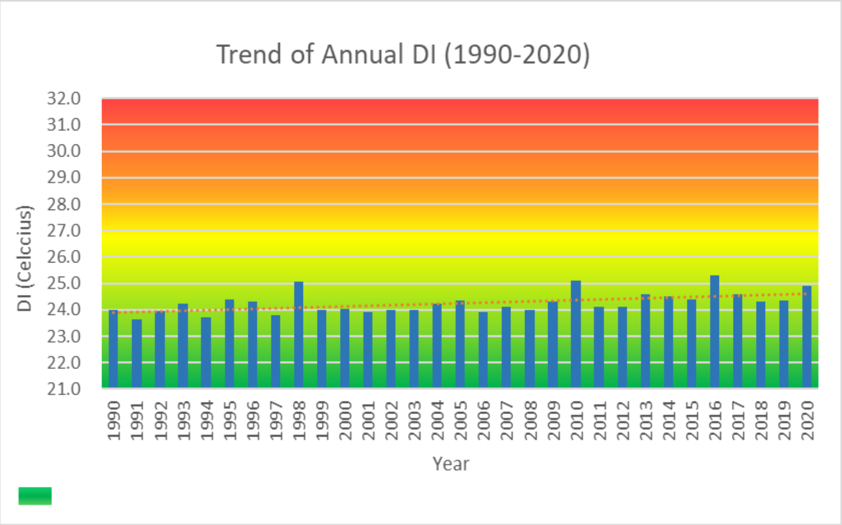

Figure 2. Trend of Annual Discomfort Index in Yogyakarta City

has an average of 36.2°C and when validating the surface temperature in the field, the value is 2.52°C lower than the conditions in the field.

Although tropical inhabitants tend to tolerate higher levels of comfort at higher temperatures due to acclimatization and variations in food, habitat, clothing, etc., (Emmanuel, 2005), the average value of LST obtained is higher when compared to some of the results of studies on thermal comfort standards in the tropics. Ellis and Navy (1952) states that comfortable /neutral conditions in Singapore are at a temperature of 26.1°C - 26.7°C. Webb (1959) states that the comfortable temperature in Singapore is at 27.2°C. In India, Rao (1952) stated that the comfortable temperature in Calcutta is 26.0°C, while in Roorkee is at 31.1°C (Nicol, 1974).

In Indonesia, so far the references to state the standard level of thermal comfort, especially outdoor, are still limited. However, there are several studies on thermal comfort in Indonesia. Karyono (2018) notes that there is research that states that the comfortable temperature range in Indonesia is around 23°C with relative humidity of 50% to 31°C with relative humidity of 60%. Meanwhile, thermal comfort in low-income settlements in Yogyakarta City is 29.1°C. In addition, in the Indonesian National Standard (SNI) 03-6572-2001 there is a classification of thermal comfort for the tropics, namely: 1) comfortable cool at an effective temperature of 20.5°C - 22.8°C; 2) optimal comfort at an effective temperature of 22.8°C - 25.8°C; and 3) comfortable warm at an effective temperature of 25.8°C - 27.1°C. However, this SNI is intended for the design of ventilation

Table 2. Threat of Thermal Discomfort Based on Land Surface Temperature

District	Min LST (°C)	Max LST (°C)	Mean LST (°C)	Classification of Threat of Threat
Danurejan	31.51	34.64	33.03	3 : High
Gedongtengen	30.53	35.33	33.09	3 : High
Gondokusuman	30.07	37.53	32.94	3 : High
Gondomanan	30.92	34.92	33.08	3 : High
Jetis	30.24	35.00	32.94	3 : High
Kotagede	27.55	34.65	31.30	1 : Low
Kraton	30.28	35.10	32.82	3 : High
Mantrijeron	29.26	33.78	31.83	1 : Low
Mergangsan	28.66	34.06	31.85	1 : Low
Ngampilan	30.58	35.53	33.26	3 : High
Pakualaman	31.37	35.55	32.88	3 : High
Tegalrejo	28.56	36.07	31.94	1 : Low
Wirobrajan	29.44	34.07	32.46	2 : Moderate
Umbulharjo	27.91	34.21	31.51	1 : Low

Table 3. Socio-population Aspect Data for Thermal Discomfort Vulnerability Assessment

District	Number of Health Facilities	Population Density (Soul/Km)^2	Percentage of Elderly Population (%)
Danurejan	13	19,445	8.34
Gedongtengen	12	20,715	9.34
Gondokusuman	36	10,812	8.57
Gondomanan	6	13,362	9.30
Jetis	13	16,106	10.01
Kotagede	24	11,260	7.93
Kraton	8	15,594	11.14
Mantrijeron	26	13,652	9.78
Mergangsan	16	12,441	9.66
Ngampilan	8	22,540	5.72
Pakualaman	9	17,033	10.61
Tegalrejo	12	12,803	9.04
Wirobrajan	17	15,957	9.53
Umbulharjo	41	8,687	7.98

and air conditioning systems in buildings. From several references to this thermal comfort level, the obtained LST of Yogyakarta City has a higher average value. Spatially, LST patterns generally resemble Urban Heat Island patterns, where the temperature peaks in the urban core and tends to decrease with increasing radial distance from the city center, including LST in Yogyakarta City (Hiemstra et al., 2017). With high urban land development intensity and dense population, urban centers have a more pronounced heat island effect, which has a major impact on thermal comfort (Yin et al., 2021).

The results of the classification of LST values show that the spatial pattern of LST formed in Yogyakarta City is a high potential for thermal discomfort (32.61°C - 33.26°C) located in the city center and experiencing expansion. However, the expansion pattern that occurs has not fully seen radial. The areas with have high potential include Danurejan, Gedongtengen, Gondomanan, Kraton, Ngampilan, Pakualaman, and further Jetis and Gondokusuman as areas of high potential expansion from the city center to the north and northeast (Table 2 and Figure 3). Wijaya and Umam (2015) stated that the center of development of Yogyakarta City's built-up land is in the northeast area of the city and one of them is located around Gondokusuman District. The increase in built-up land has a directly proportional relationship with the increase in land surface temperature (Suharyanto et al., 2023). Tian et al. (2023) also stated that changes in LULC, which refers to the increasing of built-up area over the last 30 years, are the main cause of the increase in LST and UHI in Nanjing.

Table 4. Thermal Discomfort Vulnerability Assessment Results

District	Vulnerability Score of the Number of Health Facilities Aspect	Vulnerability Score of Population Density Aspect	Vulnerability Score of the Percentage of Elderly Population Aspect	Total Vulnerability	Vulnerability Classification
Danurejan	3	3	2	8	3: high
Gedongtengen	3	3	2	8	3: high
Gondokusuman	1	1	2	4	2: moderate
Gondomanan	3	2	2	7	3: high
Jetis	3	2	3	8	3: high
Kotagede	2	1	2	5	2: moderate
Kraton	3	2	3	8	3: high
Mantrijeron	2	2	3	7	3: high
Mergangsan	3	1	3	7	3: high
Ngampilan	3	3	1	7	3: high
Pakualaman	3	2	3	8	3: high
Tegalrejo	3	1	2	6	2: moderate
Wirobrajan	3	2	3	8	3: high
Umbulharjo	1	1	2	4	2: moderate

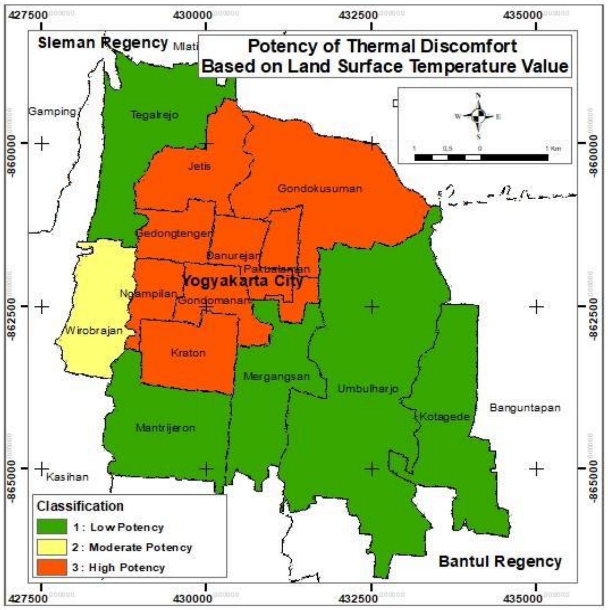

Figure 3. Spatial Pattern of Thermal Discomfort Based on LST in Yogyakarta City

3.2 Thermal Discomfort Vulnerability

The assessment of the level of vulnerability was carried out on the social aspect of population, using the variables of the availability of health facilities, population density, and the percentage of elderly population. Data on the three socio-population vulnerability variables are presented in Table 3. The results of the vulnerability assessment are presented in Table 4, Figure 4, and Figure 5. Spatially, high vulnerability in the variable availability of health facilities is located in the center and western part of Yogyakarta City. The factor for high vulnerability in this variable is the uneven availability of pharmacies by district. However, this study is also still limited to the number of facilities, not considering the spatial coverage of services by the distance factor. Meanwhile, in the percentage of elderly population variable, vulnerability is dominated in the southern region of Yogyakarta City. The variables of availability of health facilities and the percentage of elderly population are associated with the risks that can occur in public health due to heat stress. Although the relationship and influence between differences in age and productivity with thermal comfort is still poorly understood, elderly people have much higher blood pressure and are more sensitive to temperature compared to young people (Schellen et al., 2010; Wu et al., 2023).

In the population density variable, high vulnerability is found in the central part of Yogyakarta City, namely Danurejan, Gedongtengen, and Ngampilan Districts. High population density requires high consumption of land so that it will trigger high building density as well. High building density can affect environmental conditions, including environmental temperature. Building density has a directly proportional relationship with LST values (Atianta, 2020; Guo et al., 2016). Thus, areas with high population density can have a risk of thermal discomfort. Built-up land in the city center generally has materials with a low coefficient of albeddo value so that it reflects little heat and absorbs much of the heat energy received (Atianta, 2020). However, the high density of population and buildings in the center of Yogyakarta City is the result of a more intensive urbanization process that occurred in the past. Rozano and

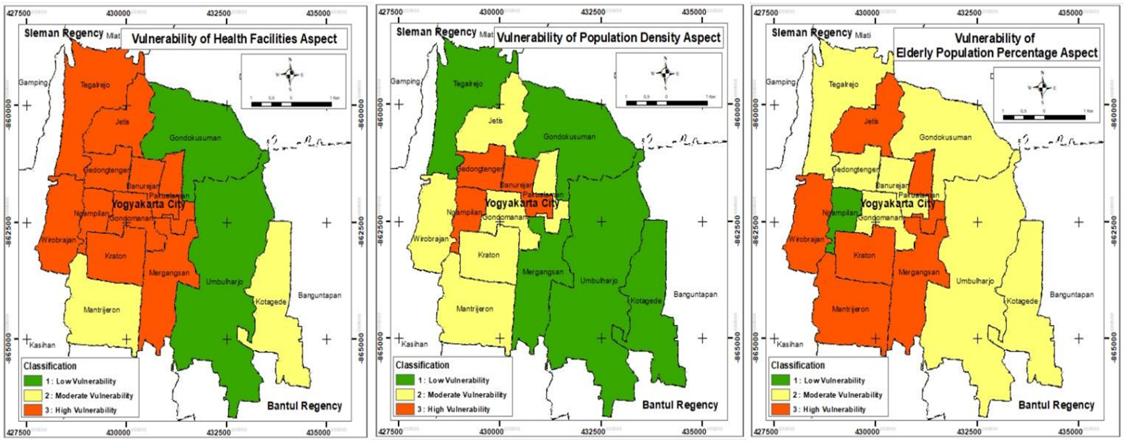

Figure 4. Distribution of Vulnerability in Three Social Aspects of Population

Table 5. Variations of Emphasis on Mitigation Aspects for High anf Moderate Location Based on The Research Variables

District With High And Moderate Priority of Thermal Discomfort Mitigation	Efforts to Restrict Surface Temperature Rise	Health Facilities Aspect	Population Density Aspect	Elderly Population Aspect
Danurejan	✓	✓	✓	
Gedongtengen	✓	✓	✓	
Gondokusuman	✓			
Gondomanan	✓	✓		
Jetis	✓	✓		✓
Kraton	✓	✓		✓
Ngampilan	✓	✓	✓	
Pakualaman	✓	✓		✓
Wirobrajan				✓

Yan (2018) suggested that after 2005, the peri-urban density of Yogyakarta City continued to increase while the density in some parts of the urban core began to decrease, leaving relatively high densities in the Districts of Gedongtengen, Danurejan, Pakualaman, Gondomanan, Kraton, Wirobrajan, parts of Mergangsan, Gondokusuman, Jetis, and Tegalrejo.

With the configuration of the results of the assessment of the three vulnerability variables, the results of the total vulnerability assessment show that Yogyakarta City consists of 2 areas of thermal discomfort vulnerability, namely in the high and medium categories, as shown in Figure 5. Of the 14 districts, there are 10 districts in the high vulnerability category and 4 districts in the medium vulnerability category. Spatially, areas with high vulnerability are located in the center and south side of Yogyakarta City, which include Danurejan, Gedongtengen, Gondomanan, Jetis, Kraton, Mantrijeron, Mergangsan, Ngampilan, Pakualaman, and Wirobrajan Districts. The pattern of heat vulnerability in Yogyakarta City, which is in the center and widens on one side, is similar to the heat vulnerability in London, United Kindom, where high vulnerability is in the center of London and widens on the east side (Wolf and McGregor, 2013).

3.3 Thermal Discomfort Mitigation Prioritization

From a risk management perspective, areas of high heat vulnerability and exposure may be at high risk of health effects (Wolf and McGregor, 2013). In this study, areas that have high potential and vulnerability are considered to have a high risk of thermal discomfort. These areas are prioritized for thermal discomfort mitigation. There are 7 districts that have a high priority are Danurejan, Gedongtengen, Gondomanan, Jetis, Kraton, Ngampilan, and Pakualaman. Medium mitigation priorities include Gondokusuman and Wirobrajan Districts. Meanwhile, low priorities include Kotagede, Mantrijeron, Mergangsan, Tegalrejo, and Umbulharjo Districts. Spatially, the areas that are the main priority for mitigation are in the center of Yogyakarta City. The seven districts have an average LST value of more than 32.60°C so mitigation requires efforts to reduce the increase in temperature. Related to the influencing vulnerability factors, this research takes factors that have a vulnerabil-

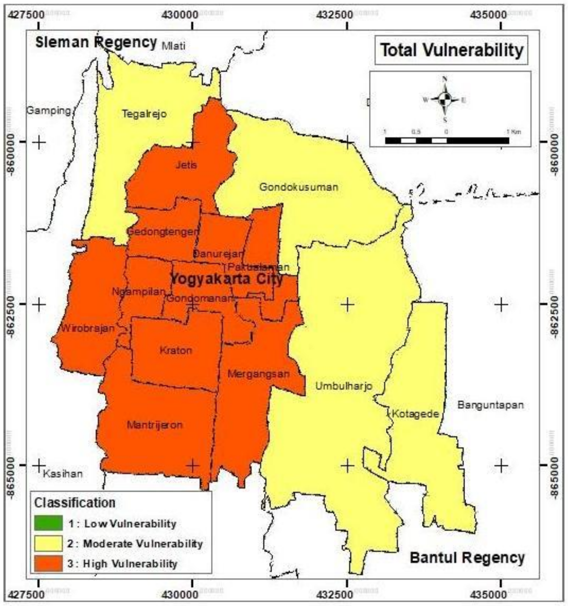

Figure 5. Distribution of Total Vulnerability to Thermal Discomfort in Yogyakarta City

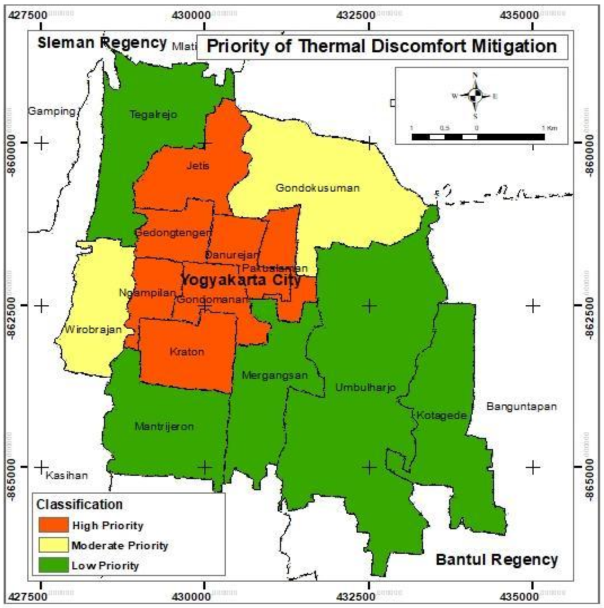

Figure 6. Distribution of Total Vulnerability to Thermal Discomfort in Yogyakarta City

ity value of 3 (high) as the basis for determining aspects that need to be emphasized in mitigation efforts in each sub-district area as presented in Table 5. Except for Gondokusuman, all of the priority districts of mitigation necessary to emphasize the aspect of facility availability in an effort to mitigate thermal discomfort. Compared with other areas that have low priority, the availability of health facilities in that district is less than in other districts. Unfortunately, this study did not analyze the level of adequacy of health facilities in relation to distance or population as well as the type and quality of services. In Danurejan, Gedongtengen, and Ngampilan Districts, the high risk factor is also caused by the relatively high population density, so this is also an aspect that needs to be emphasized in mitigation efforts. Meanwhile, aspects other than the availability of health facilities that need to be emphasized in mitigation efforts in the Jetis, Kraton, Pakualaman, and Wirobrajan Districts are related to population density.

4. CONCLUSIONS

More than half of the residents of Yogyakarta City experience thermal discomfort. Referring to temperature and relative humidity data, the annual Discomfort Index in Yogyakarta City has the potential to increase. Spatially, the pattern of potential discomfort resembles the Urban Heat Island pattern in general, namely relatively high in the center and spreading to the surrounding area although the distribution does not yet show a radial pattern, but rather towards the north and northeast. Meanwhile, from variations in the conditions of the vulnerability variables used, different spatial patterns are formed, namely high vulnerability in the central and southern parts of the city. From the variations in existing potential and vulnerability patterns, the areas with high risk are Danurejan, Gedongtengen, Gondomanan, Jetis, Kraton, Ngampilan, and Pakualaman. So, these seven sub-districts are a priority for mitigating thermal discomfort. The aspect that needs to be emphasized in mitigation in all priority areas is related to the availability of health facilities. Future research needs to analyze risk using more detailed variables and involve assessing capacity aspects. Apart from that, detailed recommendations regarding suitable forms of mitigation to be applied in each area are also interesting for further research.

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