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Ecological Evaluation of Urban Heat Island using Landsat 8 OLI/ TIR Data: Case Study of Kaduna Metropolis, Nigeria

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Abstract

The ecological impact of the Kaduna metropolis's Urban Heat Island (UHI) was assessed using Landsat 8 OLI & TIRS data from 2019. Land surface temperature (LST), a measure acquired from band 10 (Thermal Infrared band) using a Single-Channel algorithm, was used to get the temperature variation of the metropolis. The Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Build-Up Index (NDBI) were used to determine the validity of LST. The urban thermal field variance index was used to determine the metropolis level of thermal comfort (UTFVI). The result from the LST of the metropolis ranges from 26.52 °C and 41 °C with the UHI observed in zones with high concentrations of human activities. According to the UTFVI associated with UHI, 76.23 % of the metropolis has a normal to excellent microclimate for living, whereas 23.77 % has bad to worst heat stress. As a result, the public and government must develop UHI mitigation methods to improve the metropolis' quality of life.

Introduction

The term "urbanization" refers to the growing number of people who live in urban centres. According to the UN, by 2050, 64.1 % of the developing world and 85.9 % of the developed world will be urbanized (Chaolin, 2020). Rapid urbanization has had a significant impact on the environment and climate all over the world, and it has exacerbated the effects of climate change (Bazrkar et al., 2015). Urbanization results in impermeable surfaces, landscape degradation, loss of habitat, and a reduction in natural resource pathways and biodiversity (van der Walt et al., 2015). The impact of urbanization on local weather and climate is expected to be significant. Increased urbanization may have environmental consequences. It is well acknowledged and demonstrated that urbanization may have a major influence on the environment (Landsberg, Helmut E, 1981).

As urban buildings absorb and re-radiate solar radiation, as well as human heat sources, UHI is primarily caused by the huge amount of heat created. (Rizwan et al., 2008). Human activities, such as heat discharge, contribute to the heat island effect (UHI). As a result of heat exposure, the UHI can have a direct impact on health. Local weather patterns are also affected, as is local air pollution (Heaviside, 2020). As a result of the high pace of urbanization and economic development in Kaduna, the city is experiencing fast spatial expansion (Benedine & Tanko, 2017). Statistics show that there are 1,558,563 people in the city and that it is growing at around 3% per year, according to the 2006 census (NPC, 2006). This resulted in a significant change in land use. According to a study conducted by Yaro *et al.* (2017) between 1995 and 2015, built-up areas increased by 28.80%, resulting in a loss of 38.71% of vegetative cover. As a result of these changes, there has been a dramatic change in the land surface features and spatiotemporal patterns of the UHI

(Cai et al., 2016). Warming of the city Due to a photochemical reaction, UHI increases heat-related illnesses and ozone (O3) levels (Swamy *et al*., 2017). UHI is one of the urban management issues, especially in large cities, that can have a negative impact on the health and well-being of the individuals living there. (Mirzaei *et al*, 2020). In the months of March and May of the year 2019, Nigeria was hit by a series of extreme heatwaves. (Gobir *et al*, 2020). Climate change has a direct impact on the heatwave, which increases morbidity and death. It has become important to do studies on UHI to create a sustainable urban planning system in the future.

In Kaduna, there have been several studies on UHI. A study conducted by Yaro et al. (2017) assessed UHI's pattern and distribution in the Kaduna metropolis using remote sensing data and GIS, for over ten years. The study found that different land use land cover (LULC) plays an important role in the pattern of UHI within the metropolis, particularly scarcity of vegetation cover, built-up area, bare surfaces and uneven surface temperature within the metropolis.

For the Kaduna metropolis, there has been little or no research on spatial ecological evaluation index of UHI impacts utilizing an Urban Thermal Field Variance Index (UTFVI), this is the gap this study intends to fill in. Therefore, the main objectives are a) to derive land surface temperature (LST) using Landsat 8 OLI/TIRS images for the year 2019 and analyze the UHI effect of the city; and b) to study the relationship between LST, NDVI and NDBI; and c) to evaluate the ecological condition of the metropolis by UTFVI and identify high-risk locations for heat discomfort.

Study Area

Kaduna metropolis is located between latitude 10° 23' and 10° 37' N and longitude 7° 20' and 7° 32'E. The study area is tightly drawn around Kaduna's urbanized area. The area consists of four Local Government Areas, namely: Kaduna North and Kaduna South, and parts of Igabi and Chikun Local Governments and about 339.52km2 above and is situated at the centre of northern Nigeria. Urban sprawl surrounds the metropolis, with dispersed farmsteads and a moderate slope that allows for future growth.

The state shares boundaries with Abuja and Niger at the South-West, Katsina, and Zamfara at the North-West, Kano and Bauchi at the North-East, Plateau and Nasarawa at the South-East. Geographically, it is located in the northern Guinea Savanna Zone. (Odekunle et al., 2019).

The Köppen's Aw (Tropical wet and dry or savanna) climate mostly applies to the belt. There are two primary seasons in the study region each year: the rainy and the dry ones. From around April until October, the rainy season takes place. (Odekunle et al., 2019). The State's vegetation is divided between northern Guinea savannah and southern Guinea savannah. A map of the study area is shown in Figure 1.

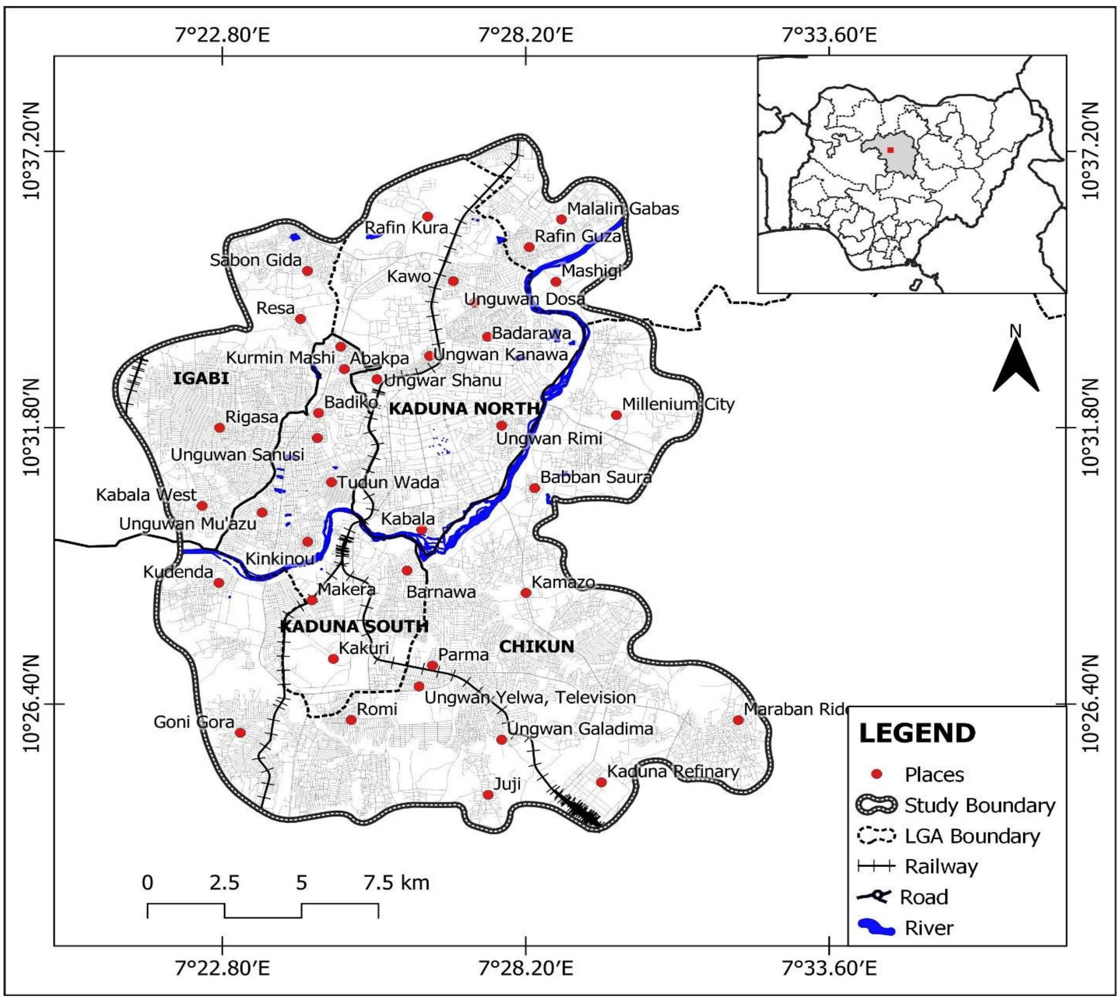

Fig. 1. Map of the study area

Source: Adapted and modified administrative map of Kaduna state

DATA AND METHOD

Data

Image selection was based on cloud cover, day, month, and year of collection for Landsat satellite images collected from the U.S. Geological Survey (USGS) Earth Explorer website collection (See Table 1). This image has undergone atmosphere corrections (Level 1T) and georeferenced to Universal Transverse Mercator (UTM), map projection (Zone 32N), WGS 84 datum, and ellipsoid. The detailed descriptions of the satellite images selected are shown in Table 1

Table 1. The detailed description of satellite images

Sensor	Path/Row	Acquisition Date	Cloud cover	Bands Used	Electromagnetic spectrum	Spectral Bands	Resolution (30 meters)
OLI/TIRS	189/53	19/11/2019	0.07%	4	Red	0.64-0.67	30
				5	Near-Infrared	0.85-0.88	30
				6	Short Wave Infrared	1.57-1.65	30
				10	Thermal Infrared	10.6-11.19	30

Source: Landsat 8 Metadata

Method

Landsat 8 (OLI/TIRS) acquired on the 19th November 2019 was used to retrieve the Land Surface Temperature (LST). The thermal band 10 with 30 meters' resolution and the projection system applied is Universal Transverse Mercator zone 32 north. A single-channel algorithm was used to derive the LST from the imagery. The spectral radiance of the top of the atmosphere, the brightness temperature was calculated from the absolute radiance values. The obtained results were converted from degree kelvin to degree Celsius.

The near-infrared band 5 and red band 4 was used to compute the Normalized Difference Vegetation Index (NDVI), while short wave band 6 and near-infrared band 5 was used to compute was Normalize Difference

Built Index (NDBI). NDVI was used to extract the surface emissivity to estimate the LST. Finally, the LST was calculated using the brightness temperature and surface emissivity. To analyze the urban heat islands at the level of the study area, indices such as NDVI and NDBI were applied to determine the correlation with the LST, while the Urban Thermal Field Variance Index (UTFVI) was used for the ecological evaluation of the urban heat island zones. QGIS 3.18.1- 'Zürich' was used for the processing of the data.

Calculation of the land surface temperature (LST)

Band 10 of Landsat 8 OLI 8 image is a thermal-infrared (TIR) band that has been commonly used for LST mapping. From the user handbook of Landsat 8 the derivation method of LST from the thermal band of a satellite image the following steps were executed in this study to retrieve the LST of the study area.

Conversion of DN to spectral radiance

To retrieve the LST, the Landsat data were first radiometrically corrected by converting the digital numbers (DN) of the band to spectral radiance. (USGS, 2019)

$$L\lambda = ML \times QCal + AL \tag{1}$$

In equation (1), Lλ is spectral radiance in Watt/(m^2srμm), ML is the band-specific multiplicative rescaling factor, QCal is the quantized and standard product pixel value (DN), AL is the band-specific additive rescaling factor. All these values can be obtained by the metadata file of the image.

Conversion of spectral radiance to brightness temperature

The spectral radiance can be converted into a light temperature in Kelvin using the following formula (USGS, 2019) as in (2)

$$BT = \frac{K2}{ln\ ln\left(\frac{K1}{L\lambda} + 1\right)} \tag{2}$$

In equation (2), K1 and K2 = band specific thermal conversion constant. For Landsat 8 OLI, K1 = 774.89 mW/cm²/sr/µm and K2 = 1321.08 Kelvin.

Calculation of the surface emissivity

One of the most widely used vegetation indices for estimating surface emissivity is the Normalized Difference Vegetation Index (NDVI). The Proportion of Vegetation (PV) of each pixel was determined from the NDVI using the following equation (Carlson & Ripley, 1997)

$$\varepsilon = 0.004 \times Pv + 0.986 \tag{3}$$

P*v* is the proportion of vegetation extracted from the NDVI as in (6)

$$Pv = \left[\frac{(NDVI - NDVImin)}{(NDVImax - NDVImin)}\right]^2 \tag{4}$$

Where, Pv = Proportion of vegetation, NDVI = NDVI Values from the Image, NDVImin = Minimum NDVI, and NDVImax = Maximum NDVI.

Land Surface Temperature (LST) retrieval

Finally, the land surface temperature (LST) is calculated according to the following formula (Weng et al., 2004)

$$LST(°C) = \frac{BT}{\left[1 + \left(\lambda \times \frac{BT}{\rho}\right) ln\, ln\, (\varepsilon)\right]} - 273.15 \tag{5}$$

Where BT = brightness temperature; λ = wavelength of the radiance emitted; ρ = h×(c/s) = 1.4388 × 10−2m K = 14388 µm K, h is the plank's constant = 6.626 × 10−34Js, s is the Boltzmann constant = 1.38 × 10−23J/K, c = velocity of light = 2.998 × 108m/s. ε is surface emissivity. For obtaining the results in Celsius, the radiant temperature is revised by adding the absolute zero (approx. -273.15°C).

The Normalized Difference Vegetation Index

NDVI (Normalized Difference Vegetation Index) is one of the most widely applied vegetation indices to strengthen the vegetation information to calculate NDVI is calculated by the following formula (Lu et al., 2009). NDVI values ranging from -1 to +1 where water bodies tend to have minus NDVI values, and green healthy vegetation tends to have positive NDVI values.

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (6)$$

Where:
NDVI = Normalized Difference Vegetation Index;
NIR = Near Infrared band of the Landsat 8 Image; and
RED = Red band of the Landsat 8 Image; and

The Normalized Difference Built-up Index

NDBI (Normalized Difference Build-up Index) is one of several widely used indices to strengthen building information and extract the built-up land from urban areas. NDBI is calculated by the following formula: (Lu et al., 2009). The NDBI values also ranging from -1 to +1 and positive values highlight the built-up urban areas

$$NDBI = \frac{SWIR - NIR}{SWIR + NIR} \quad (7)$$

Where:
NDBI = Normalized Difference Built-up Index;
SWIR = Short Wave Infrared Band of the Landsat 8 Image; and
NIR = Near Infrared of the Landsat 8 Image

LST Model Validation

The modelled LST values were verified using NDBI and NDVI. Verification uses both qualitative and quantitative techniques. The NDBI, NDVI, and LST data were compared visually and quantitatively using a correlation matrix. The LST values should be related to the NDBI values positively and the NDVI values negatively (Chen et al., 2013)

The Urban Thermal Field Variance Index

The Urban Thermal Field Variance Index (UTFVI) was applied to evaluate the urban surface temperature quantitatively. LST layer is used to derive the UTFVI which can be calculated using formula (8) by (Liu & Zhang, 2011).

$$UTFVI = \frac{T_S - T_{mean}}{T_{mean}} \quad (8)$$

Where UTFVI is the urban thermal field variance index, Ts is the LST (°C), and Tmean is the mean LST (°C)

Results and Discussion

The Accuracy Validation of LST Retrieval

The theoretical relationships between LST, NDVI, and NDBI, LST variables were qualitatively verified by visual interpretations of these variables NDVI, NDBI, and LST in the images as in (Figure 2). Therefore, areas with high NDBI values (i.e., Built-up area) have high LST (LST > 39°C) and low NDVI values as expected while, areas with high NDVI (i.e. vegetation cover) have low LST (LST < 29 °C) and low NDBI values as well. Furthermore, the water bodies have low LST values (LST = 26 °C), with the lowest NDVI (NDVI= -0.35) and NDBI (NDBI = -0.18).

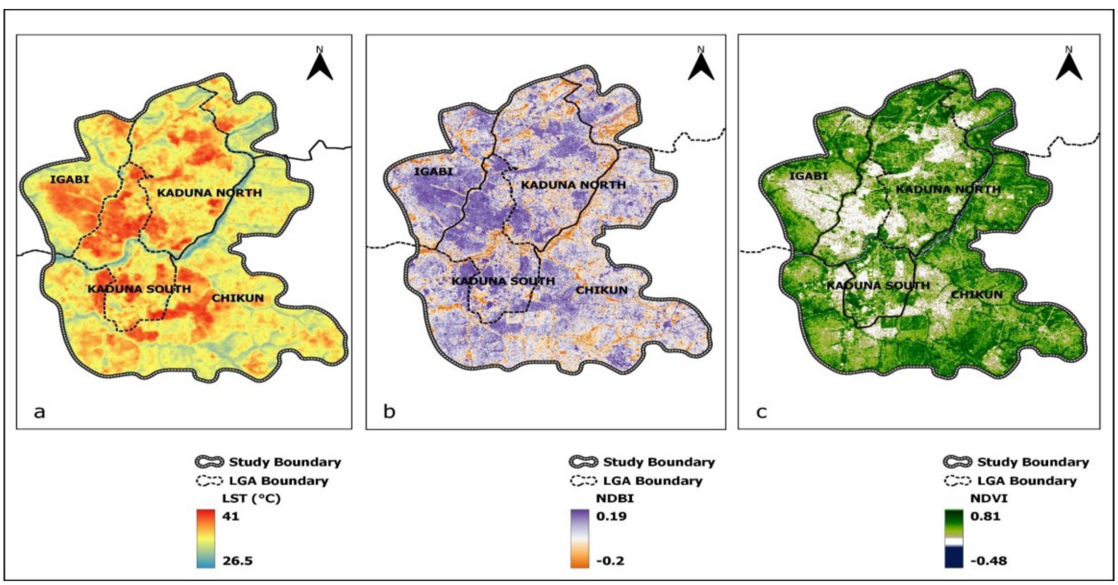

Figure. 2 LST and corresponding NDVI and NDBI values of the study area, (a) LST map (b) NDBI map (c) NDVI map

The quantitative validation of LST, NDVI, and NDBI layers was done using a correlation analysis which was based on pixel-based image comparison. Table 2. the results obtained by the correlation matrix, the strongest relationship (i.e., r = -0.70) was obtained between NDVI and NDBI layers. This correlation between NDBI and NDVI shows a very strong negative relationship which indicates a serious decline in green vegetal cover and an increase in a built-up area in the study area. The correlation between LST and NDVI shows a moderate negative relationship (i.e., r=-0.56) while the correlation between LST and NDBI shows a strong positive relationship (i.e., r=0.68).

Table 2. Correlation between LST, NDBI, and NDVI

	LST	NDBI	NDVI
LST	1	0.68	-0.56
NDBI	0.68	1	-0.70
NDVI	-0.56	-0.70	1

Source: Data analysis 2021

The strong positive relationship between LST and NDBI values show that built-up areas contribute to the increase of UHI and can strengthen the UHI effect. While the negative relationship between LST and NDVI values shows the cooling effect of the vegetal cover area such as farmland, green spaces, and parks. This result indicates that the UHI impact can be reduced through the increase in green space within the metropolis.

Analysis of Urban Heat Islands in Kaduna metropolis

The spatial distribution of the LST in the Kaduna metropolis is shown in Figure 3a. Temperatures range from 26.52 ° C and 41 ° C for the minimum and maximum respectively. The mean for the LST is 34.45 ° C.

Table 3. showing the area covered and percentage of LST

LST (° C)	Area (km^2)	Percentage
26 - 31	11.32	3.33%
31 - 35	178.93	52.70%

35 - 41	149.27	43.96%
	339.52	100.00%

Source: Data analysis 2021

The influence of UHI in a metropolis is determined by the population number and the type of building pattern. In the metropolis, from northeast, southeast and at the centre which divides the metropolis have less population, water bodies and green space, compared to the location of north, south, west, and the central business district of the metropolis which explains the high values of LST.

In general, table 3 shows how the metropolis undergoes varied temperatures from 31 - 35°C, account for (52.7%) of the total area of the metropolis. These LST values are found in the area with green space and where settlements are not congested. The values of the LST range from 35 > °C which account for (43.96%) of the total surface of the metropolis, these zones generally represent the area with a high concentration of human activities (congested settlement, commercialized area, industrial complex). Areas with LST < 31°C, account for (3.33 %) of the area, however, they are mostly covered by water (i.e., River and wetlands).

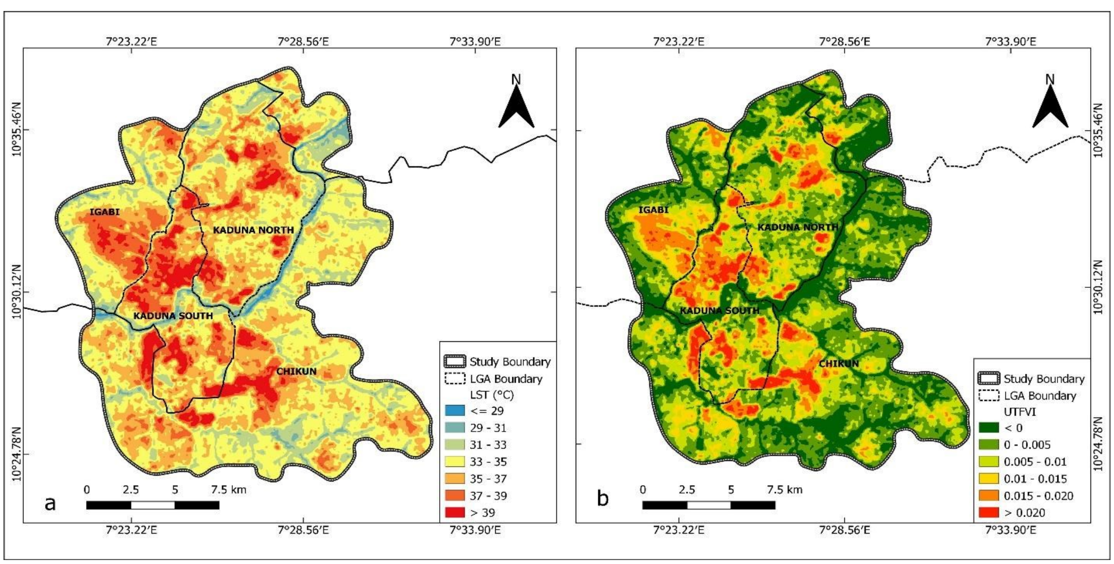

Figure 3. (a) Land surface temperature (LST) of the Kaduna metropolis. (b) Ecological evaluation index (UTFVI) of the Kaduna metropolis.

The Ecological Evaluation of Kaduna Metropolis Urban Heat Islands

The quantitative ecological evaluation of the UHI effects in the Kaduna metropolis is shown in Figure 3b. Urban Thermal Field Variance Index (UTFVI) is a way of quantifying the urban ecological condition of quality of life in terms of thermal comfort with the impact of UHI.

Table 4 showing the area covered and percentage of ecological evaluation

Ecological Evaluation Index	Area (km^2)	Percentage
Excellent	73.75	21.72%
Good	106.79	31.45%
Normal	78.29	23.06%
Bad	39.55	11.65%
Worse	28.84	8.49%
Worst	12.31	3.63%
	339.52	100.00%

Source: Data analysis 2021

The Urban Thermal Field Variance Index can be subdivided into six levels following six different ecological assessment indices (Liu & Zhang, 2011). Table 5. indicates the specific thresholds for the six levels of the Urban Thermal Field Variance Index for example, there are areas with ideal microclimate (UTFVI < 0) and areas with high heat stress (UTFVI > 0.02) in the city.

Table 5. Interpretation of the quantitative assessment index for the ecological effects

Urban Thermal Field Variance Index	Urban Heat Island phenomenon	Ecological Evaluation Index
<0	None	Excellent
0 -0.005	Weak	Good
0.005 - 0.01	Middle	Normal
0.01 - 0.015	Strong	Bad

0.015 - 0.02	Stronger	Worse
0.02 >	Strongest	Worst

Sources: (Liu & Zhang, 2011)

Table 4 shows that finding reveals that outlying peripheries areas around the metropolis which are in dark green are considered to be excellent and account for 21.72% of the total area. While the areas identified in green and bright green are good and normal ecological indexes, they account for 31.45% and 23.06%, respectively (i.e., UTFVI < 0.01) are areas with lesser development, that are usually located at the peripheries of the metropolis and has proximity to water bodies, wetlands, and green spaces.

A study conducted by Isioye *et al*., (2020) That thermal comfort in the Abuja Municipality is quite important. The data suggests that the city's outlying peripheries are more ecologically friendly than the city's central centre, according to the findings. UHI effects that are environmentally harmful or severe affect 40% of the population, demonstrating the necessity for continuing UHI mitigation efforts.

Furthermore, due to a lack of vegetal cover and existing UHIs, areas distinguished in yellow (i.e. UTFVI>0.01) have the bad ecological evaluation index and account for 11.65 % of the metropolis's total area, while areas in orange have the worse scenario and account for 8.49 %, while areas identified in red have the worst-case scenario and account for 3.63 % having the strongest UHI phenomenon. This are mostly commercial and urbanized area.

In summary, the UTFVI detected no temperature discomfort in 76.23 % of the study area, according to the ecological assessment of UHI impacts. Only 23.77 % of the metropolis was found to have various degrees of thermal discomfort and heat stress.

CONCLUSION

The LST assessment using Landsat 8 OLI & TIR, with the use of a single-channel algorithm indicated the varying spatial distribution of the UHI phenomenon in the Kaduna metropolis. It was revealed that the spread of the UHI phenomena has a strong significant relation with the land use land cover. Water bodies, vegetative cover, wetland, and green space have all been shown to reduce the impacts of UHI, while densely populated areas, commercialized areas, and congested settlements have all been shown to increase the effects of UHI.

Furthermore, the UTFVI, which was used to measure the quality of life through the relationship of thermal comfort and UHI intensity were detected. The Kaduna metropolis is subjected to extreme weather conditions, including the worst circumstances of thermal discomfort as well as the optimal microclimate for a good quality of life. The microclimate for living in the metropolis is normal to excellent at 76.23 %, which is a positive indicator. However bad to worst heat stress condition, 23.77% is observed in the central business district and core metropolis area and its surrounding, indicating the potential of the UHI phenomenon on the quality of life in the metropolis. It is therefore important for the public and government to adapt UHI mitigation strategies to strengthen the quality of life in the metropolis.

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