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Ecological Appraisal of Urban Heat Island in Zaria, Nigeria

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ABSTRACT

With rapid population growth, urbanization, coupled with other anthropogenic activities, Zaria, Nigeria experiences, UHI, with a steady increase in surface and atmospheric temperatures over the years. This study evaluates the UHI in the study area and its effect on the ecology, using Landsat ETM+ and OLI/TIRS remotely-sensed data, between 2009 and 2019. The satellite data were used to derive NDVI and LST for 2009, 2015 and 2019 while the UHI effects on the quality of urban life was evaluated using UTFVI. Results indicate that there is an increase of 2.44°C in the mean surface temperature in Zaria between 2015 and 2019, with a slight overall decrease of 1.88°C between 2009 and 2019. The hot spot of UTFVI were found mainly in the bare, uncultivated lands, built-up areas, especially the commercial and industrial districts. These areas are the most vulnerable to UHI phenomenon and negatively affected in ecological quality. In general, a large portion of the city experiences ecologically worse UHI effects, indicating a need for continued UHI mitigation efforts.

1. INTRODUCTION

Urbanization influences local meteorological and climatic conditions. One of these environmental influences or impact is the formation of Urban Heat Islands (UHI) in affected areas (Khallef et al. 2020; Streutker 2002), which directly inspires environmental degradation. Moreover, rising temperatures due to global climate change is amplified by the effect of UHI (Della-Marta et al. 2017). UHI is the surplus temperature near the ground or urban areas, which is usually higher than those of nearby or surrounding areas (Voogt and Oke 2003). This phenomenon is widely analyzed and is one of the major themes of urban climatology, particularly its impact on human health (Huang and Lu 2018). UHI has been regarded as an example of anthropogenic climate modification within the field of urban climate (Arnfield 2003). Rapid urbanization is the greatest factor for the formation of UHI, which is a matter of global concern. This urbanization and the fact that temperatures are rising globally are motivating the urgency to study and understand urban areas and their climatic implications (Kaur and Pandey 2019).

While built-up areas and bare surfaces have been shown to accelerate the effect of UHI, green space and water bodies reduce the UHI intensity (Amiri et al. 2009). Land Surface Temperature (LST) is a parameter used to quantify UHI. It is the temperature of the land surface which can be measured when the surface is in contact with a measuring instrument.

Studying the thermal differences between urban and rural areas, retrieving LST and UHI have been made easier with the use of satellite remote sensing, aided by GIS. Several researches have been carried out to show some thermal comfort indices for measuring the effect of UHI intensity. These include: physiological equivalent temperature, temperature humidity index, wet-bulb globe temperature and urban thermal field variance index (UTFVI) (Guha et al. 2018; Kakon et al. 2010; Matzarakis et al. 1999; Willett and Sherwood 2012; Zhang 2006). However, UTFVI is the most commonly used index for the ecological evaluation of urban environment due to its relationship with surface temperature (Alfraihat et al. 2016; Isioye et al. 2020; Liu and Zhang 2011). It is therefore imperative to determine the thermal comfort level of every city in this regard.

The pattern, trend and characteristics of urbanization in Nigeria have been alarming. Town and cities have grown unbelievably with pace of urbanization in Nigeria showing high growth rates of 5% - 10% per annum (Egunjobi 1999). Over the years, Zaria has experienced a rapid population growth and urbanization, with the population growing from 698,000 in 2006 to over a 970,000 people in 2019 (Humanitarian Data Exchange 2020). With the accelerated rate of urbanization, UHI has developed more significant as it

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has severe impact on urban development and human living environment (Chen et al. 2009). Meanwhile, increasing urban heat in Zaria and environs presents a significant health risk for the growing population and the related heat stress is likely to escalate with the increase in surface temperature.

This study seeks to utilize remotely sensed data and GIS to examine the distribution and changes in LST of the study area and analyze the impact of UHI phenomenon on the quality of urban life in the study area, using UTFVI. UHI phenomenon was investigated over the study area using Landsat 7 and 8 images covering the period 1999 through 2019 at 3 epochs. The relationship between LST and NDVI was also examined to investigate the effect of vegetation on dynamics of surface temperature. Satellite data with temporal, spatial and spectral characteristics makes it possible to study temperature changes spatio-temporally.

2. METHOD

2.1. Description of the Study Area

The study area is the city of Zaria in northern Nigeria which comprises of Zaria and Sabon Gari Local Government Areas in Kaduna state. It is located between latitudes 10° 57' and 11° 15' north of the equator and between longitudes 7° 35' and 7° 48' east of the Central Meridian. It occupies a total land area of approximately 545.77 km^2 at an average elevation of 644m above mean sea level. Zaria experiences a typical tropical climate and it records a mean daily maximum temperature of about 38°C and a mean daily minimum of about 16°C (Meteoblue 2020). Zaria has a population of 975,153, making it the second largest city in Kaduna state, Nigeria (Worldometer 2020). Due to urban sprawl and population growth being experienced in Zaria, there is a corresponding loss of vegetation which exerts a significant influence on the micro-climate of the area. A map of the study area is shown in Figure 1.

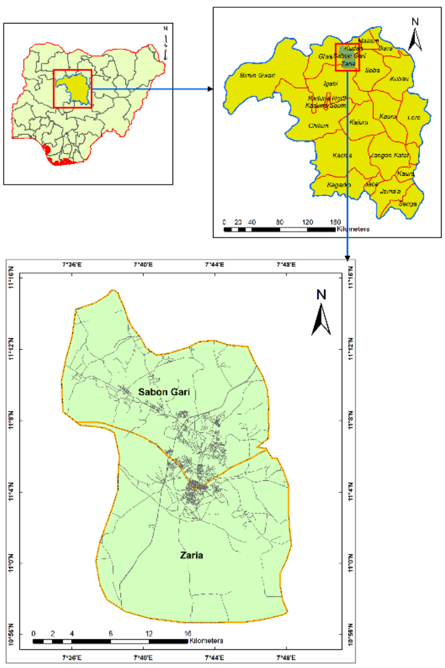

Figure 1. Map of the study area

2.2. Data Acquisition and Pre-processing

Cloud-free Landsat 7 ETM+ and Landsat 8 OLI/TIRS images were obtained from the earth explorer platform of the USGS website (earthexplorer.usgs.gov) for the years 2009, 2015 and 2019. The details of the Landsat images selected for this study are presented in Table 1.

Table 1. Details of the Landsat data used in this study

Satellite/ sensor	Path/ Row	Acquisition date	Resolution (Spectral/TIRS)
Landsat 7(ETM+)	189/52	04/03/2009	30m/60m
Landsat 8 (OLI/TIRS)	189/52	29/03/2015	30m/100m
		20/02/2019	30m/100m

The Landsat images were all subjected to radiometric calibration to produce scaled and comparable data and to reduce scene-to-scene variability, while the Landsat 7 (ETM+) image was corrected for scan line error. The images were then subset for further analyses, using the administrative map of the study area.

2.3. Derivation of NDVI

The Normalized Difference Vegetation Index (NDVI) is calculated from the reflectance values of the visible red and near infrared bands. The NDVI can be calculated using equation (1).

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (1)$$

NIR and RED in Landsat images are the reflectance in the near-infrared and visible red portion of Electromagnetic spectrum respectively.

2.4. Retrieval of LST

The following procedures were carried out to retrieve the LST of the study area. First, the digital numbers (DN) of the thermal bands were converted to at-satellite spectral radiance using the following equation.

$$L_\lambda = M_L \times QCal + A_L, \quad (2)$$

Where L_λ = at sensor spectral radiance in Watt/(m^{2}srμm); M_L = the band-specific multiplicative rescaling factor from the metadata; QCal = the quantized and standard product pixel value (DN); and A_L = the band-specific additive rescaling factor from the metadata

The spectral radiance converted from pixel DN values above was then used to compute Top of Atmosphere (TOA) brightness temperature (T_B) as follows.

$$T_B = \frac{K_2}{ln\, ln \left(\frac{K_1}{L_\lambda} + 1\right)} \quad (3)$$

Where T_B = the effective at-satellite temperature; K1 and K2 are two calibration constants, which are supplied by the metadata of Landsat images.

Subsequently, the emissivity-corrected LST (in Celsius) was computed as follows (Stathopoulou and Cartalis 2007).

$$LST(^{o}C) = \frac{T_B}{\left[1 + \left(\lambda \times \frac{T_B}{\rho}\right) ln\, ln\,(\varepsilon)\right]} - 273.15 \qquad (4)$$

Where λ = the wavelength of emitted radiance; $\rho = h\times(c/s) = 1.4388 \times 10^{-2}$m K = 14388 μm K; h = the plank's constant (6.626×10^{-34}Js); s = the Boltzmann constant (1.38×10^{-23}J/K) ; c = velocity of light = $2.998 \times 10^{8} m/s$; ε = thermal emissivity.

In this study, the NDVI threshold method was used to obtain surface emissivity (ε) (Sobrino et al., 2004) while the proportion of vegetation (Pv) was computed from the NDVI according to (Carlson and Ripley 1997).

2.5. The Urban Thermal Field Variance Index (UTFVI)

The urban thermal field variance index (UTFVI) is commonly used to show the UHI effect or the thermal comfort level of an urban area. It can be estimated by equation (5) (Zhang et al. 2006).

$$UTFV = \frac{T_s - T_m}{T_s} \qquad (5)$$

Where T_s is the LST and T_m is the mean of the LST of the whole study area.

In order to examine the UHI effect, the UTFVI values are divided into six categories, each with the corresponding interpreted ecological evaluation index (Zhang et al. 2006), as shown in Table 2.

Table 2. Threshold values of urban thermal field variance index and ecological evaluation index

UTFVI	UHI phenomenon	Ecological Evaluation Index
< 0	None	Excellent
0 - 0.005	Weak	Good
0.005 - 0.010	Middle	Normal
0.010 - 0.015	Strong	Bad
0.015 - 0.020	Stronger	Worse
> 0.020	Strongest	Worst

3. RESULTS AND DISCUSSION

3.1. Spatial Pattern of LST

The spatial distribution of the LST of the study area derived from Landsat images are shown in Figure 2. Table 3 shows the statistical summary of LST distribution in Zaria in the study period.

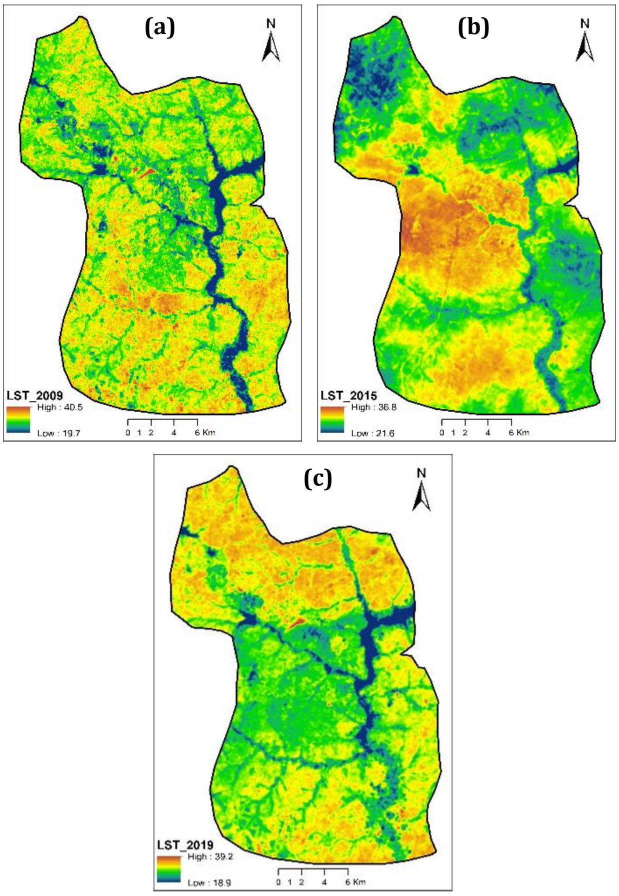

Figure 2. LST maps of Zaria in (a) 2009, (b) 2015, and (c) 2019

Table 3. Summary of LST distribution in Zaria between 2009 and 2019

Year	Min. Temp. (°C)	Max. Temp. (°C)	Mean Temp. (°C)
2009	19.74	40.48	33.87
2015	21.62	36.76	29.55
2019	18.95	39.16	31.99

From the results obtained, it was observed that overall, there was a 1.88°C decrease in mean surface temperature in the study area between 2009 and 2019, though the mean temperature increased by 2.44°C between 2015 and 2019. Generally, higher surface temperatures are found in the densely populated city center and bare lands, especially as seen in 2015, while the lower temperatures are along the water bodies, wetlands and the vegetated areas. The city center is the most populated area with a beehive of anthropogenic activities and release of greenhouse gases. These activities produce impervious surfaces, which in turn rise the surface temperature of this area compared to the surrounding localities. In 2019 though, the city centre is cooler with lower LST values while higher LST values are observed at bare surfaces and uncultivated farmlands in the northern and southern parts of the city.

3.2. Ecological Evaluation of Zaria using UTFVI

In this study, the ecological evaluation of the study area was carried out for the two extremes of the study period: 2009 and 2019, to investigate the change in thermal comfort level of the area. The UTFVI which measures urban ecological quality of life in terms of the degree of thermal comfort in relation to the existence of the UHI phenomenon was used for the evaluation. Figure 3 shows the ecological assessment of the effects of UHI in Zaria.

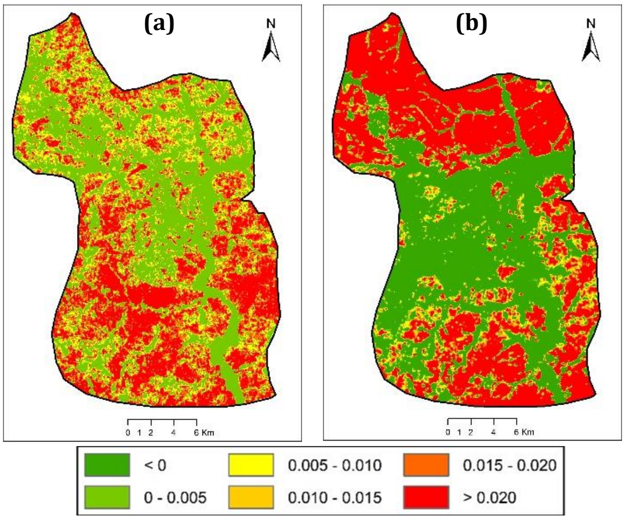

Figure 3. UTFVI maps of Zaria in (a) 2009 and (b) 2019

The effect of UHI were identified based on the degree of thermal comfort that is associated with the existence of UHI. From results obtained, it was found that the city experiences two extremes of thermal comfort: areas of thermal stress (UTFVI > 0.02) and areas of good micro climate (UTFVI < 0). Table 4 shows the quantitative distribution of the UTFVI threshold in the study area in 2009 and 2019.

Table 4. Ecological evaluation index of Zaria

UTFVI	UHI phenomenon	Ecological Evaluation Index	Area occupied (km^2) 2009	Area occupied (km^2) 2019
< 0	None	Excellent	0	231.66
0 - 0.005	Weak	Good	203.59	22.15
0.005 - 0.010	Middle	Normal	104.79	24.93
0.010 - 0.015	Strong	Bad	0	27.11
0.015 - 0.020	Stronger	Worse	100.71	27.91
> 0.020	Strongest	Worst	136.65	211.98

Results show that areas that enjoy optimal thermal conditions (i.e. UTFVI < 0 ≤ 0.005) are areas with water bodies, vegetation and wetlands. In 2009, 203.59 km^2 of the total land mass has been weakly impacted by UHI, thus enjoying good thermal comfort level whereas 231 km^2 of the study area enjoyed excellent thermal comfort in 2019, with no impact of UHI. 136.65 km^2 and 211.98 km^2 are areas worst hit by UHI effect (UTFVI > 0.020) in 2009 and 2019 respectively. These areas are mostly bare lands and sparsely cultivated lands since the Landsat images were taken in the dry season.

Just as observed in the LST distribution, there is a significant improvement in areas experiencing excellent thermal comfort (UTFVI < 0) in 2019 as compared to 2009. This is evident in the decrease in surface temperature between 2009 and 2019. The largest portion of Zaria city experiences optimal thermal condition for habitation probably due to the presence of trees within residential areas in the city centre and its proximity to a dam and other wetlands. Higher UTFVI values occur in the extreme northern and southern regions of the study area. These areas are thermally stressed and consist of the bare lands and other impervious surfaces.

Generally, UHI phenomenon was more evidently seen in 2019, with large areas in the periphery of the city presenting extreme high UTFVI values (> 0.020). Accordingly, the ecological evaluation index also got worse in this year.

4. CONCLUSION

This study has demonstrated the capability of using remotely sensed dataset and Geographical Information System (GIS) to investigate and monitor the effect of UHI on a particular geographical location. It was also discovered that examining temperature dynamics can aid in analyzing the urban environment and consequently help in decision making processes for city development.

In this study, Landsat ETM+ and OLI/TIRS satellite data were processed to analyze the surface temperature dynamics in Zaria and subsequently study the thermal comfort level of the city using UTFVI. Results show a decrease in mean surface temperature in Zaria between 2009 and 2019 (from 33.87^{o}C to 31.99^{o}C). This may be as a result of the tree planting projects in the city in recent years, irrigation farming in the dry season, presence of wetland and the city's proximity to a dam. Though an increase in surface temperature was recorded in the city centre between 2009 and 2015 as a result of population increase and urban sprawl.

Two extremes of thermal comfort levels were observed from results of analyzing the city's UTFVI as the city experiences both good/excellent conditions of thermal comfort and worst conditions of thermal discomfort. The hot spot of UTFVI were found mainly in the city's commercial and industrial districts, bare surfaces and uncultivated farmlands at the periphery of the city. Other areas adversely affected by the UHI phenomenon include some residential areas around the city and other impervious surfaces such as pavements, asphalt roads etc. These are likely areas that are susceptible to UHI. It was observed in 2019 that a large portion of the city centre experiences excellent microclimate for living, which is encouraging.

However, there is a dire need to mitigate the effect of UHI in Zaria, Nigeria by increasing tree and vegetative cover, installing green roofs, and using cool pavements.

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