Spatio-Temporal Assessment of the Influence of Urban Change on Land Surface Temperature

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Keywords: Built-up area, Land Surface Temperature, Suleja, Urban Change and Urban Heat Island.

SUMMARY

The urban growth rate in most of Nigeria's communities is alarming, which has led to the conversion of farmlands and forest lands into built-up areas and an increase in urban heat. This study assesses the urban heat in Suleja LGA of Niger State, Nigeria. The specific objectives of this study were to analyse both the trend of urban change and the average land surface temperature (LST) for the study area between 1987 and 2019 to assess the influence of urban change on land surface temperature. The relationship between the Normalised Difference Built-up Index (NDBI), Normalised Difference Vegetation Index (NDVI), and LST was further ascertained to achieve the aim of the study. Remote sensing techniques were employed to analyse the data downloaded from United States Geological Survey archives. The study reveals that farmlands were significantly converted to urban land, contributing to the effects of urban heat in the study area. The rapid urban change in the study area also increased Suleja's land surface temperature within the study epochs. The average land surface temperature of the study area surged from 13.24°C in 1987 to 36.39°C in 2019. In response to the escalating land surface temperature in Suleja, the research advocates for preserving forested areas and promotes the implementation of urban landscape planning initiatives within the Suleja Local Government Area.

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1. INTRODUCTION

Urban areas are envisaged to triple by 2030 to accommodate the rising global population increase (U.N., 2018). The envisaged urban change in terms of the spatial change in built-up areas and the population growth is said to be responsible for the declining vegetation cover in urban areas of the world. It is believed that due to the increased population and demand for land for physical development, nearly 4 million hectares of vegetation cover are lost in Africa annually (Igini, 2022). The loss of vegetation covers due to urban change is often accompanied by increased land surface temperature, frequently leading to urban heat islands (Kabano, 2021; Kafy et al., 2022).

Urban heat island is a phenomenon where a city experiences much warmer temperatures in the core than its peripheral settlements as a result of replacing natural land cover in the urban area with impermeable surfaces, buildings, and other surfaces that absorb and retain heat (Voogt and Oke, 2003). The definition of urban heat island shows that the increasing urban population's land use can influence that region's land surface temperature. On the other hand, the definition of an urban heat island also indicates that an increase in land surface temperature can be influenced by the size and form of the city (Giridharan and Emmanuel, 2018). Therefore, examining how urban size (population increase and built-up increase) and land use influence urban heat islands is pertinent, especially since the heat intensity effect of solar radiation varies significantly across urban and rural areas (Ajayi et al., 2023).

However, different urban planning approaches have been used to mitigate a city's increasing urban heat island. These approaches include the strategic urban planning approach, urban landscape planning and the sustainable city planning approach (Bohn, 2023; Gago et al., 2013; Li et al., 2019; MacLachlan et al., 2021). All these planning approaches were geared towards optimally replacing vegetation and conserving green spaces in the urban area. In recent times the sustainable city planning approach and the urban landscape planning approach were proposed for the Suleja local government area of Niger State in the 2012 Integrated Development Plan and the 2019 – 2023 Niger State Development Blue Print.

The sustainable and urban landscape planning approaches were proposed to mitigate the environmental problems brought about by the rapid urbanisation in Suleja. Due to lack of political will by the Niger State government, both the Integrated Development Plan of 2012 and the 2019 – 2023 Niger State Development Blue Print were yet to be implemented. The inability of the government to implement the Integrated Development Plan, Niger State Blue Print and to review the outdated Masterplan encourages the increasing urban population to convert any available land into physical development. This guided physical development action further exacerbated the urban heat Island in Suleja.

Many studies have been conducted to explore the impacts of urbanisation on urban land surface temperature. These extensive studies focus on either the effect of land use (Farid et al., 2022; Igun and Williams, 2018; Moazzam et al., 2022) or the impact of Population density (John et al., 2024; Mallick and Rahman, 2012) on Urban heat Island (Ajayi et al., 2023). Despite these extensive studies, there are still gaps in integrating the land use characteristics and population dimension in assessing urban heat islands. Against this background, this study assesses urban heat in the Suleja local government area of Niger State with the following specific objectives: (I) to analyse the trend of urban change and the land surface temperature between 1987 and 2019; (II) to determine the influence of urban change and land surface temperature; and (III) to Determine the relationship the Normalised Difference Built-up Index and the land surface temperature.

2. STUDY AREA AND SCOPE

Suleja Local Government area is one of the four major urban areas of Niger State (Niger State Urban Support Programme [NSUSP], 2012**).** Since the relocation of Nigeria's Federal Capital Territory (FCT) from Lagos to Abuja in 1991, the study area has recorded unprecedented urban growth due to its proximity to the new capital city (Adeleye et al., 2023b). The proximity to the FCT also gave Suleja Local government area priority in terms of its infrastructural development above other local government areas in Niger State (Niger State Regional Development Plan, 1979). The study area is located between Latitude 9º 08′ 00.16′N to 9º 16′ 00.17′N and Longitude 7º 08′ 00.13″ E to 7º 12′ 00.13″ E (See Figure 1). This study's urban change scope was limited to population density and land use characteristics of the Suleja local government area.

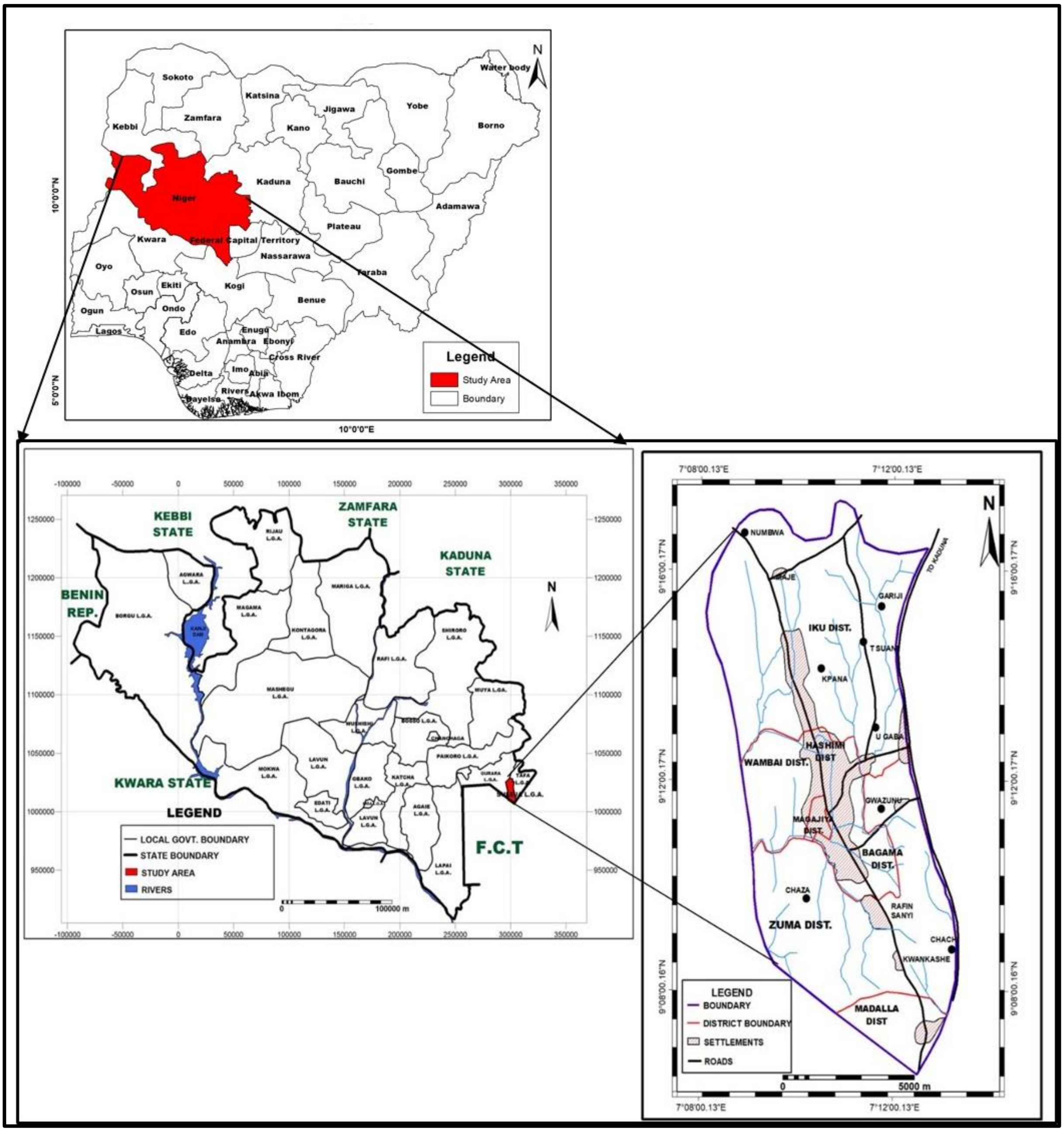


Figure 1: Suleja Local Government Area in the National Context

3. METHODOLOGY

3.1 Sources of Data and Image Processing

Georeferenced imageries for the study area were downloaded from the United States Geological Survey (earthexplorer.usgs.gov) on path 189 and row 54. Four sets of imageries were downloaded from different sensors: the thematic mapper (1987), the enhanced thematic mapper (1999), the enhanced thematic mapper plus (2007), and the Operational land imager (2019). The "gap mark" associated with the 2007 image downloaded was corrected using the "gap mask" of 2007. The "gap marks" were filled out using the "fill no data tool" on QGIS 3.24 software. Bands 3,2,1, 4,3,2 and 5,3,2 were used to form the false colour composite for Landsat 4 (1987), Landsat 5 and 7, and Landsat 8, respectively. The area of interest of the respective years (1987, 1999, 2007 and 2019) was "clipped", and five sample sets were created for each. The sample sets were built-up areas, waterbodies, vegetation, Barren surfaces, and farmland. The sample sets created were further classified through a maximum likelihood supervised classification algorithm on QGIS 3.24 software.

3.2 Trend of Change between 1987 and 2019

The land change model was used to determine the transition matrix of the classes of land uses created for this study. The urban change intensity model by Qiuying et al. (2015) which comprises five indices (very low [< 0.1], low [0.1 – 0.2], moderate [0.2 – 0.4], rapid [0.4 – 0.7] and highly rapid [≥ 0.7]) was used to determine the intensity of change in the study area between 1987 and 2019. The urban change intensity model is expressed as:

$$UCII = \left(\frac{A2 - A1}{N}\right) * \frac{100}{TA}$$

Where: A1 is the urban areas at the beginning of a period, A2 is the urban areas at the end of a period, and N is the number of years between the end of a period (A2) and the beginning (A1). At the same time, T.A. is the total land area.

3.3 Calculating Land Surface Temperature (Urban Heat) between 1987 and 2019

The thermal bands (Landsat 4, 5, 7 and 8) of clipped imageries were used to estimate the urban heat of Suleja between 1987 and 2019. Band 6 was used to estimate the urban heat (land surface temperature) for the study area for 1987, 1999 and 2007 (at different wavelengths). Meanwhile, the thermal bands 10 and 11 at different wavelengths were used to estimate the urban heat for 2019 (Table 1). The urban heat for the study area was determined in four stages. In the first stage, the digital numbers were converted to spectral radiance using the mathematical equation by USGS (2019), which is expressed as:

$$L_\lambda = \left(\frac{LMAX_\lambda - LMIN_\lambda}{QCAL_{Max} - QCAL_{Min}}\right)(QCAL - QCAL_{Min}) + LMIN_\lambda \qquad (1)$$

Where:
L_λ = At Senor spectral radiance in [W/ (M^2 sr μm)]
$QCAL$ = Digital number (Landsat Image [DN])
$QCAL_{Min}$ = Minimum quantised calibrated pixel $LMIN_\lambda$
$QCAL_{Max}$ = Maximum quantised calibrated pixel $LMAX_\lambda$
$LMIN_\lambda$ = Spectral at sensor level that is scaled to $QCAL_{Min}$[W/ (M^2 sr μm)]
$LMAX_\lambda$ = = Spectral at sensor level that is scaled to $QCAL_{Max}$ [W/ (M^2 sr μm)]

The spectral radiance of the area of interest of the respective years (1987, 1999, 2007 and 2019) was converted to "At-Satellite brightness temperature" in the second stage, in Kelvin (T.B.) by using the inverse of the Planck function (USGS, 2019) which is expressed as equation (2):

$$TB = \frac{K2}{\ln\left(\frac{K_1}{L\lambda} + 1\right)} \qquad (2)$$

Where: $T_B$is “At-Satellite brightness temperature”, L_λ is the top of atmosphere spectral radiance (Watts/(M^2 * srad * µm)), K_2 and K_1 are band-specific thermal conversion constants from the metadata. The results deduced from this equation were further converted to degrees Celsius by subtracting “273.15” from the results in Kelvin. The land surface emissivity was determined at the third stage using the mathematical model expressed as E = 0.004 (Proportion of Vegetation) + 0.986, where P.V. is $(\text{NDVI - NDVImin /NDVImax - NDVImin})^2$. At the final stage, the urban heat of Suleja was calculated using the signal window algorithm, which is expressed as LST=BT/1 + W* (BT/P) * ln (e)

Where:

B.T. is at Satellite temperature,
W is the wavelength of emitted radiance (11.5µ),
E is the emissivity and
P is h*c/s (1.438* $10^{\wedge}$- 2 m k)/14380

Zha et al. (2005) equation was used to calculate the study area's normalised difference built-up area index (NDBI). The short-wave and near-infrared bands were used to calculate the NDBI. The Zhe et al. (2005) equation used is expressed as:

$$NDBI = \frac{\text{SWIR}-\text{NIR (Near Infrared)}}{\text{SWIR}+\text{NIR (Near Infrared)}} \qquad (3)$$

Table 1: Metadata of the Imageries Used

Year	Reference Path & Row	Landsat 4 (T.M.)	Band 6	Band 6	Date Captured
1987	P189R54	Radiance Maximum	12.50	-	21/12/1987
		Radiance Minimum	1.238	-	
		Quantize Cal Maximum	255	-	
		Quantize Cal Minimum	1	-	
		Thermal constants (K1)	671.62	-	
		Thermal constants (K2)	1284.30	-	
1999	P189R54	**Landsat 5 (TM)**	**Band 6**	**Band 6**	27/12/1997
		Radiance Maximum	15.303	-	
		Radiance Minimum	1.238	-	
		Quantize Cal Maximum	255	-	
		Quantize Cal Minimum	1	-	
		Thermal constants (K1)	607.76	-	
		Thermal constants (K2)	1260.56	-	
2007	P189R54	**Landsat 7**	**Band 6**	**Band 6**	09/12/2007
		Radiance Maximum	17.0	12.65	
		Radiance Minimum	0.00	3.20	
		Quantize Cal Maximum	255	255	
		Quantize Cal Minimum	1	1	
		Thermal constants (K1)	666.09	1282.71	
		Thermal constants (K2)	666.09	1282.71	

2019	P189R54	**Landsat 8**	**Band 10**	**Band 11**	04/01/2019
		Radiance Maximum	22.00	22.00	
		Radiance Minimum	0.10	0.10	
		Quantize Cal Maximum	65535	65535	
		Quantize Cal Minimum	1	1	
		Thermal constants (K1)	774.89	480.89	
		Thermal constants (K2)	1321.08	1201.14	

Source: United States Geological Survey, 1987, 1999, 2007, 2019

The Linear regression model was used to ascertain the relationship between urban change and land surface temperature.

4. FINDINGS AND DISCUSSIONS

4.1 The Trend of Urban Change and The Land Surface Temperature between 1987 and 2019

The dynamics in land use of Suleja between 1987 and 2019 suggest that an increase in anthropogenic activities had implications on all the land uses within the study area (Table 2). As a result of the increase in anthropogenic activities, the land area of the built-up regions expanded from 7.14 km^2 (1987) to 39.41 km^2. The expansion in built-up areas implies a 451.96 per cent increase in the built-up areas within the 32-year study period. The analysis also reveals a decrease in the forest land as the year evolves. As a result of the increase in human activities, 65.96% of forest land was lost between 1987 and 1999. The loss in forested areas increased between 1987 and 2007, with an additional loss of 0.9 Km^2 (66.68% between 1987 and 2007). The study further reveals that 74.96% of forest land was lost between 1987 and 2019. The loss of forest land in the study area exposes residents to a worsened threat of urban heat (Kabano et al., 2021; Rahaman et al., 2022; Van de Walle et al., 2022).

Table 2: Trend of land use change in Suleja Between 1987 and 2019

Class	**1987 (KM^2)**	**%**	**1999 (KM^2)**	**%**	**2007 (KM^2)**	**%**	**2019 (KM^2)**	**%**
Built-up	7.14	2.98	11.75	4.92	18.51	7.75	39.41	16.50
Bare Surface	1.20	0.50	2.84	1.19	2.08	0.87	1.77	0.74
Waterbody	13.69	5.73	32.86	13.76	22.55	9.44	21.09	8.83
Farmland	92.19	38.60	148.95	62.37	154.16	64.55	146.23	61.23
Forestland	124.59	52.17	42.41	17.76	41.51	17.38	30.30	12.69
Total	238.81	100	238.81	100	238.81	100	238.81	100

The transition matrix in Table 3 shows how Forest land and farmland were transformed into other land uses in Suleja between 1987 and 2019. The transition matrix reveals that due to increased anthropogenic activities, forest land and farmlands were converted into Built-up areas, Farmland, Bare surface, and waterbody. The transformation of these land uses (Forest land and farmland) led to the loss of vegetal cover, which can exacerbate urban heat in the study area (Kabano et al., 2021; Rahaman et al., 2022; Van de Walle et al., 2022). Within the study epochs, 2.58 km^2 of forest land was transformed into the built-up area. In comparison, increased human activities converted 0.54 km2 of forest land to bare surfaces. The increased human activities in the study area led to land degradation, resulting in artificial ponds and increased waterbodies. Between 1987 and 2019, 28.41 Km^2 of forest land area was converted to waterbodies. The most significant land use that gained the forest land was farmland, as 115.17 km^2 of forest land was transformed into farmland. The analysis further reveals that farmland transformation was the major contributor to urban lands (30.15 km^2).

Table 3: Transition Matrix of Suleja Between 1987 and 2019

		1987 - 1999		**1999 - 2007**		**2007 - 2019**		**Total**
'From Class'	'TO Class'	Area Km^2	%	Area Km^2	%	Area Km^2	%	Km^2
Forest land	Built-up Area	1.60	0.67	0.19	0.08	0.79	0.33	2.58
	Farm Land	70.39	29.48	12.64	5.29	32.14	13.46	115.17
	Bare Surface	0.47	0.20	0.02	0.01	0.05	0.02	0.54
	Waterbody	23.64	9.90	1.69	0.71	3.08	1.29	28.41
Farmland	Forest land	7.29	3.05	14.08	5.90	11.36	4.76	32.73
	Built-up Area	6.13	2.57	8.21	3.44	15.81	6.62	30.15
	Bare Surface	1.93	0.81	1.26	0.53	1.11	0.46	4.30

Using the urban change intensity model by Qiuying et al. (2015) with the corresponding indexes of < 0.10, 0.10 – 0.20, 0.21 – 0.40, 0.41 – 0.70, and ≥ 0.71 for very low, low, moderate, rapid, and highly rapid, respectively. The urban change in the study area was an edge and outlying pattern (Adeleye et al., 2023), with a rapid intensity of urban change from 1987 to 2019. The rapid intensity of urban change in the study area signifies an increase in impervious surface and vegetation depletion, increasing a region's temperature (Van de Walle et al., 2022). Table 4 further explains that the urban change in Suleja intensified from Low urban change between 1987 and 1999 to highly rapid between 2007 and 2019.

Table 4: Urban Change Intensity in Suleja from 1987 to 2019

Year	**1987 -1999**	**1999 - 2007**	**2007 - 2019**	**1987 - 2019**
Annual Average Rate of Urban Change (%)	5.20	7.54	9.04	3.13
Urban Change Intensity Index	0.16	0.36	0.73	0.42
Category of Urban Change	Low	Moderate	Highly Rapid	Rapid

An increase in urban population is consequential to increased physical development, affecting urban temperature (Klein and Anderegg, 2021; Tandon and Verma, 2021). This scenario clearly plays out in Suleja within the study epoch, and the analysis reveals that the urban temperatures of the study area increase with population growth and human activities. The study shows that the maximum urban temperature of Suleja was as low as 19.99^{o}C with a minimum of 6.48^{o}C in 1987 with an urban population of 53,731. As the Built-up areas and population increase, the urban temperature also increases (Table 5). The highest urban temperature in the study area was recorded in 2019, with a maximum temperature of 43.83^{o}C and a minimum temperature of 28.95^{o}C. The land surface temperature of Suleja within the period under study is presented in Figure 2.

Table 5: Land surface temperature (LST) of Suleja between 1987 and 2019

Year	Minimum temperature (^{0}C)	Maximum temperature (^{0}C)	Mean (^{0}C)	Urban Land Km^2	Urban population
1987	6.48	19.99	13.24	7.14	53,731
1999	25.82	37.22	31.52	11.75	184,586
2007	24.22	42.48	33.35	18.51	223,942
2019	28.95	43.83	36.39	39.41	296,803

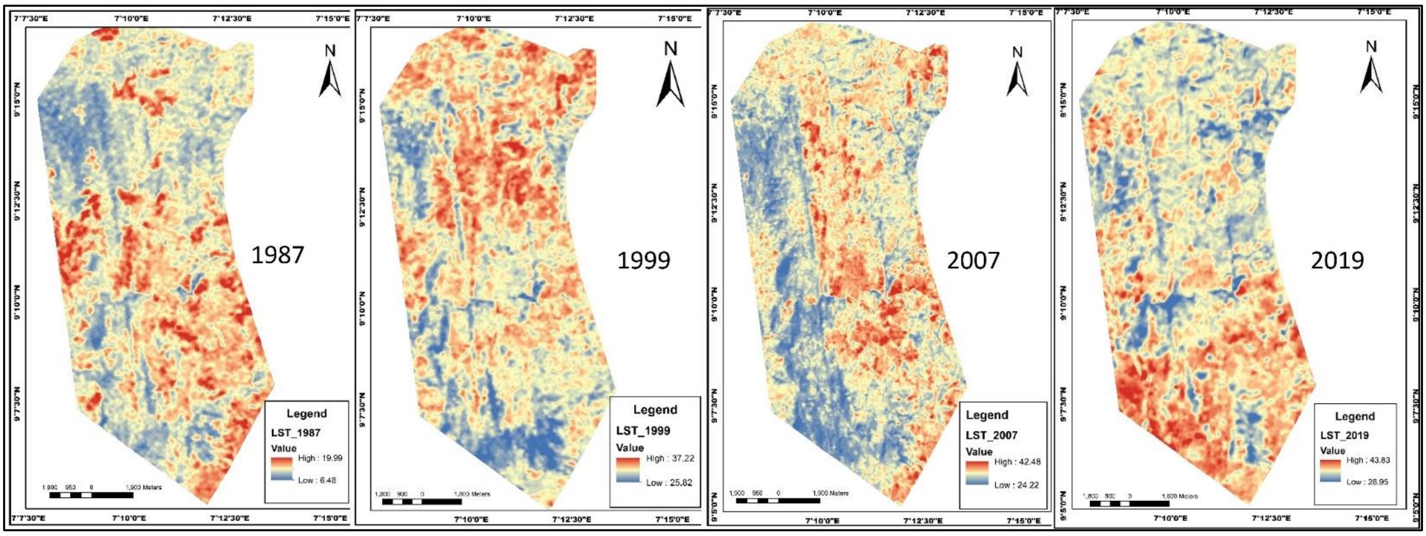


Figure 2: Land Surface Temperature of Suleja between 1987 and 2019

4.2 The Influence of Urban Change on Land Surface Temperature

A multiple linear regression analysis was performed to examine the influence of urban change (Built-up and Population density) on the variable LST, with urban change being the independent variable and LST the dependent variable. The regression model showed that the urban change variables (Built-up Area and Population Density) explained 99.43% of the variance from the variable LST. An ANOVA was used to test whether this value differed significantly from zero. The present sample found that the effect was significantly different from zero, F=87.39, p = <.001, R^2 = 0.99. The regression coefficients reveal that when all independent variables are zero, the value of the LST is 14.69. If the values of the variable 'built-up area' and 'population density' change by one unit, the value of the variable LST changes by -0.41 and 0.04, respectively (Table 6).

The standardised coefficients beta further reveals that the variable 'Population density' has the greatest influence on the variable LST of the two independent variables measured. This implies that as the population density of the Suleja Local government area increases, the LST also increases. The result of this finding was also in line with the findings of John-Nwagwu et al. (2024); Mallick and Rahman (2012) revealed that high population density is one of the main factors influencing high land surface temperature in both Delhi, in India and Lokoja, Nigeria.

Table 6: Summary of the Multi-Regression Analysis

R	**R^2**	**Adjusted R^2**	**Standard Error of the Estimate**		
1	0.99	0.98	1.43		
Model	df	F	P-Value		
ANOVA					
Regression	2	87.39	<.001		
Coefficients					
	Unstandardised Coefficients	Standardised Coefficients			
Model	B	Beta	Standard error	t	p
(Constant)	14.69		1.76	8.36	.076
Built-up Area	- 0.14	- 0.53	0.12	-3.41	.182
Population Density	0.04	1.42	0	9.23	.069

4.3 The Relationship between the Normalised Difference Built-up Index, Normalised Difference Vegetation Index and the Land Surface Temperature.

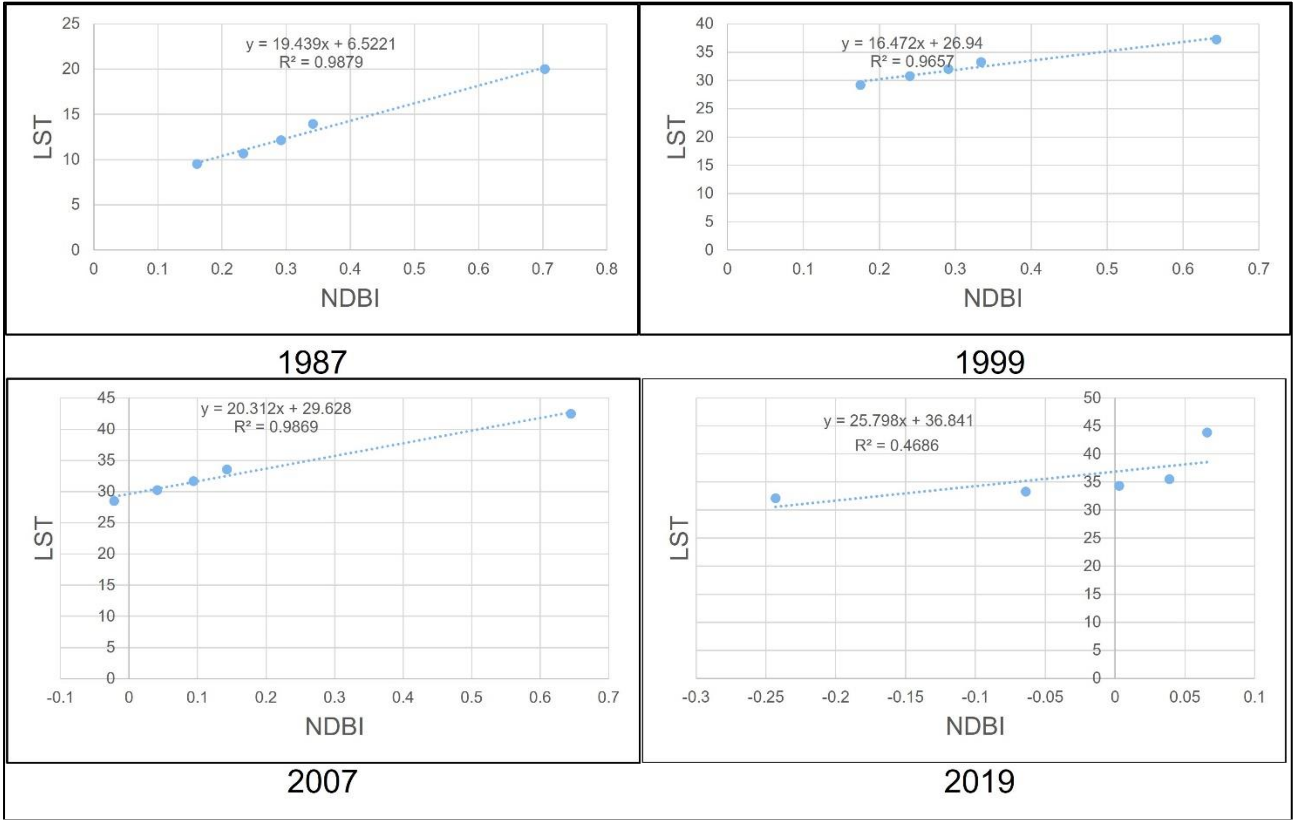
The analysis in Table 7 shows a significant positive correlation between LST and NDBI in Suleja between 1987 and 2019. The Pearson correlation index of 0.9939, 0.9827, 0.9934, and 0.6827 was recorded for 1987, 1999, 2007 and 2019, respectively. The linear relationship between LST and NDBI further implies that an increase in built-up areas is consequential to the rise in Suleja's urban heat. This finding also affirmed the findings of Chen et al. (2015), Fabeku et al. (2018), Ajayi et al. (2023), Adeleye et al. (2023a), who opined that expansion of built-up areas in a region will increase the intensity of the urban heat in that region. The relationship between NDBI and LST is shown in the line graph in Figure 3.

Table 7: Relation between LST, NDBI and NDVI

	Relationship between LST & NDBI		**Relationship between LST & NDVI**	
Year	Coefficient of determinant (r^2)	Coefficient of Correlation (r)	Coefficient of determinant (r^2)	Coefficient of Correlation (r)
1987	0.9879	0.9939	- 0.6907	- 0.8311
1999	0.9657	0.9827	- 0.6894	- 0.8303
2007	0.9869	0.9934	- 0.6264	- 0.7914
2019	0.4686	0.6827	- 0.5437	- 0.7374

A strong negative correlation was recorded in Suleja between NDVI and LST, which implies that Suleja's LST is sensitive to changes in the vegetation index (Table 7). Weng et al. (2004) and Ajayi et al. (2023) also agreed that the more abundant the vegetation cover, the lower the

LST. Applying this assertion to Suleja would mean that a reduction or an increase in the vegetation index will impact the land surface temperature of the core of the urban area.



1987

1999

2007

2019

Figure 3: Relationship between NDBI and LST

5. CONCLUSIONS AND RECOMMENDATIONS

The rapid intensity of urban change recorded in Suleja between 1987 and 2019 explains that ample vegetation covers were converted to built-up areas. The influence of urban change on LST in Suleja concludes that population density and urban change are significant factors that impact LST in the urban area. The relationship between NDBI, NDVI, and LST indicates that abundant vegetation cover is critical to reducing high urban heat islands. This study, therefore, recommends that the government protect Suleja's forest reserves to avoid encroachment by developers seeking land for physical development. The proposed Integrated Development and the Niger State Development Blue Print should be implemented to achieve urban landscape planning that preserves green spaces in the urban area. Furthermore, optimal vegetation replacement should be encouraged by the Niger State Ministry of Environment to reduce urban heat islands.

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BIOGRAPHICAL NOTES

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