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## Article

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Journal of Urban Management

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*Suggested Citation:* Jain, Shweta et al. (2020) : Urban heat island intensity and its mitigation strategies in the fast-growing urban area, Journal of Urban Management, ISSN 2226-5856, Elsevier, Amsterdam, Vol. 9, Iss. 1, pp. 54-66, <https://doi.org/10.1016/j.jum.2019.09.004>

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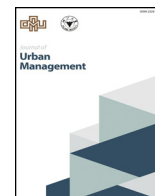
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# Urban heat island intensity and its mitigation strategies in the fast-growing urban area



Shweta Jain<sup>a</sup>, Srikanta Sannigrahi<sup>a,\*</sup>, Somnath Sen<sup>a</sup>, Sandeep Bhatt<sup>b</sup>,  
Suman Chakraborti<sup>c</sup>, Shahid Rahmat<sup>a</sup>

<sup>a</sup> Department of Architecture and Regional Planning, Indian Institute of Technology, Kharagpur, West Bengal, 721302, India

<sup>b</sup> Department of Geology & Geophysics, Indian Institute of Technology Kharagpur, West Bengal, 721302, India

<sup>c</sup> Center for the Study of Regional Development (CSRD), Jawaharlal Nehru University, New Delhi, 110067, India

## ARTICLE INFO

### Keywords:

Land surface temperature  
Biodiversity  
Urban heat island intensity  
Remote sensing  
NDVI  
Nagpur

## ABSTRACT

Climate change especially rising temperature in the urban areas has become a major focus of attention worldwide because of the impacts having on human beings, biodiversity, and urban ecosystem. Time series Landsat (TM and ETM+) satellite data products have been employed in this study to quantify the spatiotemporal Land Surface Temperature (LST) and Urban Heat Island (UHI) intensity for the year of 2000, 2005, 2010 and 2015, respectively. Biophysical characteristics of the city have been assessed through Normalized Difference Vegetation Index (NDVI), Normalized Difference Built-up Index (NDBI) and Normalized Difference Bareness Index (NDBaI). The thermal behavior of the city varied distinctly. Seasonal LST and biophysical composition of the city has been analyzed to explore the temperature and greenness sensitivity across the city region. The per capita electricity consumption of the city was positively correlated with the surface LST for both summer and autumn/spring season. A relative brightness temperature approach was employed to examine the nature of UHI across the city. It is evident from the observation that the temperature is very high within the city core as well as certain surrounding areas of the city, especially on the southern side. The temperature is comparatively lower on the western side of the city than the eastern region. Certain peripheral regions, however, show a higher temperature. This can be due to the development taking place in the outer areas of the city and destruction of vegetation in the outlying parts of the city. Studied NDVI indicates that vegetation in the city is not balanced. It is high in the western part which maybe because of the locations of different academic institutions, botanical gardens, seminary hills, agricultural land, etc. Whereas, the eastern part is devoid of vegetation. Also, the areas in the periphery, especially near the airport and Ambajhari Lake, has very low vegetation. The bareness is also high in the peripheral regions. Result also shows that street-based heat intensity mitigation helps for urban planning.

## 1. Introduction

Urbanization process accelerates rapidly in the recent era due to high population growth and excessive rural, urban migration (United Nations, 1997; Wu, 2004). In India, the level of urbanization increased from 27.81% in 2001 to 31.16% in 2011 (Census of India, 2011). Urbanization has led to distinct landscape changes, deteriorate the environmental condition which degrades the quality

\* Corresponding author.

E-mail address: [srikanta.arp.iitkgp@gmail.com](mailto:srikanta.arp.iitkgp@gmail.com) (S. Sannigrahi).

<https://doi.org/10.1016/j.jum.2019.09.004>

Received 23 February 2019; Received in revised form 25 August 2019; Accepted 20 September 2019

Available online 15 October 2019

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of life, pollute the ambient air and deteriorate the quality of water (Wu, 2004; Amiri, Weng, Alimohammadi, & Alavipanah, 2009; Bokaie, Zarkesh, Arasteh, & Hosseini, 2016; Adeyeri, Akinsanola, & Ishola, 2017). The unprecedented changes of landscape and human appropriation significantly dismantle the energy exchange between the earth surface and the atmosphere leads to increase the urban ambient temperature that deviates from the surrounding non-urbanized areas (Buyantuyev & Wu, 2010). This phenomenon called Urban Heat Island (UHI) that creates distinct thermal and microclimatic conditions in urban areas which affect the lives of the inhabitants and the overall environment of the urban areas (Voogt & Oke, 2003). Meanwhile, heat waves in an urban area mainly occurs in the island zones due to the high concentration of surface temperature (Chen, Zhao, Li, & Yin, 2006). This can be attributed to the periods of abnormally hot weather creating uncomfortable conditions for the habitats, the severe impact of these heat waves can lead to aggravation of health problems and even death (EPA 2008). In hot and dry climate zones, the combined impact of weather and heatwaves have a considerable impact on the lives of the inhabitants (Tran et al., 2017). UHI in some Indian cities in recent studies was found to be 3.3 °C in Chennai (Lilly & Devadas 2009), 8.2 °C in Delhi (Mohan and Kandya, 2015), 2.2 °C in Guwahati (Borbora & Das, 2014). The urban thermal environment is thus one of the major urban environmental issues leading to a need for urban planning which focus on strategies for creating comfortable living conditions for the citizens.

Remote sensing approaches were found fruitful in several studies in estimating Land Surface Temperature (LST) and UHI phenomenon over urban ecosystem (Asgarian, Amiri, & Sakieh, 2015; Guo, Wu, Xiao, & Chen, 2015; Mohan & Kandya, 2015; Perugini et al., 2017; Li et al., 2014; El-Zeiny and Effat, 2017). The moderate resolution multispectral Landsat satellite products; i.e. Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) thermal data of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) have been used for estimating spatiotemporal LST (Amiri et al., 2009; Chun & Goldmann, 2014; Deng & Wu, 2013a, b; Wu, Jenerette, Buyantuyev, & Redman, 2011; Guo et al., 2015; Sannigrahi, Rahmat, Chakraborti, Bhatt, & Jha, 2017, 2018). Previous research suggested that thermal characteristics and landscape pattern associated with the LST are the results of composition and configuration of land use and land cover (Buyantuyev & Wu, 2010; Chakraborti et al., 2019; Zhou, Huang, & Cadenasso, 2011). Deng & Wu (2013a,b) suggested that vegetation abundance, impervious surface, and soil functions are the key determinant in LST variation across the urban area. Therefore, these biophysical components are subject to seasonal variations and assumed to be nonlinear with LST (Chen et al., 2006). Chen et al. (2006) found seasonal variations in landscape pattern metrics are correlated with the LST. On the other hand, Buyantuyev and Wu (2010) studied linked between the LST and changes in land use and land cover classes are associated with income, population density.

Mainly three types urban heat island can be categorized as *canopy layer heat island* (CLHI), *boundary layer heat island* (BLHI) and *surface urban heat island* (SUHI) from different layers of urban atmosphere and surface properties (Voogt & Oke, 2003; Yuan and Bauer, 2007). Most urban surfaces have a high thermal capacity. CLHI and BLHI are mainly associated with atmospheric heat islands, whereas SUHI represented the surface thermal properties and known as land surface temperature (Yuan and Bauer, 2007). Land surface temperature (LST) can be used for effective climate modelling, climate-sensitive urban planning and regional and global energy balance as it is determined by the earth skin radiance and reflectance, ultimately controls the efficiency of heat exchange between the earth and atmosphere (Chayapong & Dasananda, 2012; Gago, Roldan, Pacheco-Torres, & Ordóñez, 2013). The nighttime temperature within the city increased due to heat transfer process as in the daytime (Arnfield, 2003).

The study is primarily aimed at analyzing the urban thermal environment of Nagpur and provide mitigation measures for the thermal changes in the urban area through the study of urban heat island effects in Nagpur. Therefore, the objectives of the study are (1) to study and understand the urban heat island, its causes, and impacts, (2) to analyze the relationship between urbanization pattern and thermal changes and (3) to study the mitigation measures for thermal changes.

## 2. Materials and methods

### 2.1. Study area

Nagpur city is located in Maharashtra state, between 21°45 N to 20°30 N and 78°15 E to 79°45 E at the geographical centre of India. It is one of the major cities in central India and is one of the fastest-growing cities influenced due to urbanization (Katpatal, Kute, & Satapathy (2008); Kotharkar & Surawar (2015)). With a population of 2.405 million, this city is rapidly urbanizing, and this growth is bound to affect the urban environment. Nagpur has a hot and dry climate with dry conditions prevailing for most of the year. The local climate is characterized by sharp temperature (ranges from 37°C- 45 °C in April–May to 10 °C in December–January) and precipitation (ranges from 1000 mm to 1800 mm) difference. The city experiences extreme summers with maximum temperature up to 44 °C. The phenomenon of heat waves is also prevalent in this region leading to uncomfortable living conditions especially during summer when the city experiences harsh temperature effects. Urbanization may further add up to the problems. Hence actions are required for reducing the temperature in this region for creating comfortable living conditions for the citizens (Fig. 1).

### 2.2. Extracting land surface temperature and UHI from landsat image

The LST can be derived from the thermal bands of the Landsat TM, ETM+ and Landsat 8 satellite imagery products. The methodology involves firstly the correction of different atmospheric noises have been minimized using the ENVI Fast Line-of-sight Atmospheric Analysis of Hypercubes (FLAASH) atmospheric correction module. Secondly, the extraction of the land surface emissivity (LSE) of the study area to derive LST. Thirdly, biophysical indicators were derived from the different band combinations (Amiri et al., 2009; Fu & Weng, 2016; Li, Zhou, & Ouyang, 2013; Owen, Carlson, & Gillies, 1998).

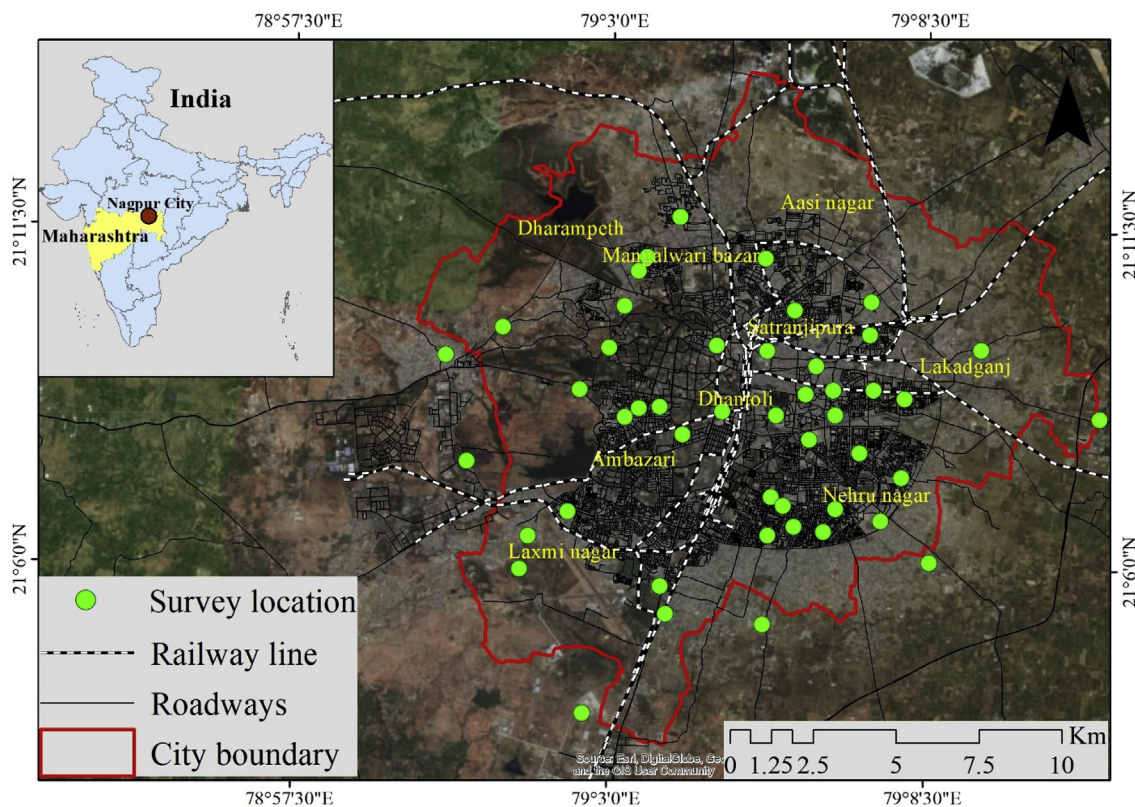


Fig. 1. Location of the study region.

**Table 1**  
Description of the UHI intensity classes.

Relative brightness temperature (TR)	UHI intensity class
-0.02–0.07	very weak heat island
0.07–0.10	weak heat island
0.10–0.15	moderate heat island
0.15–0.20	strong heat island
0.20–0.40	very strong heat island

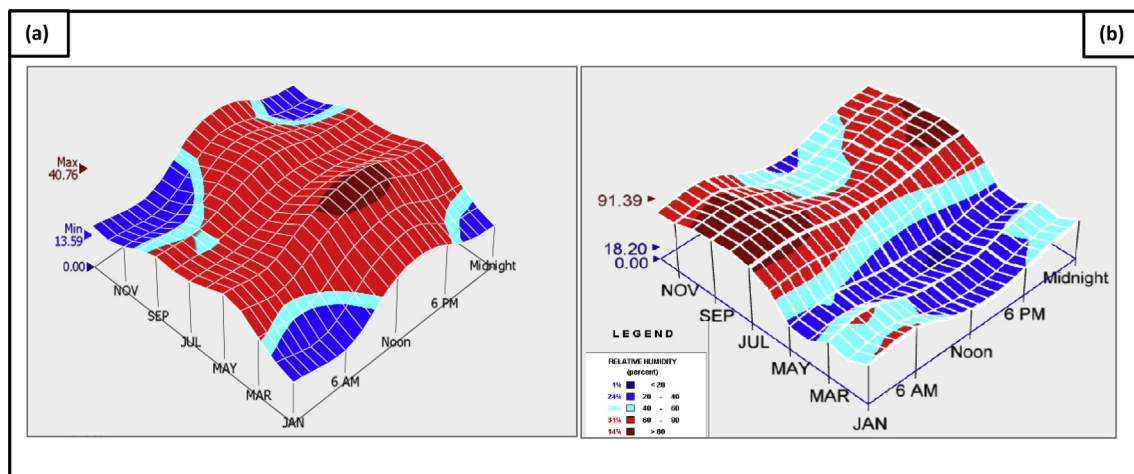


Fig. 2. Distribution of (a) Annual dry bulb temperature (°C) and (b) annual relative humidity (%) in Nagpur city.



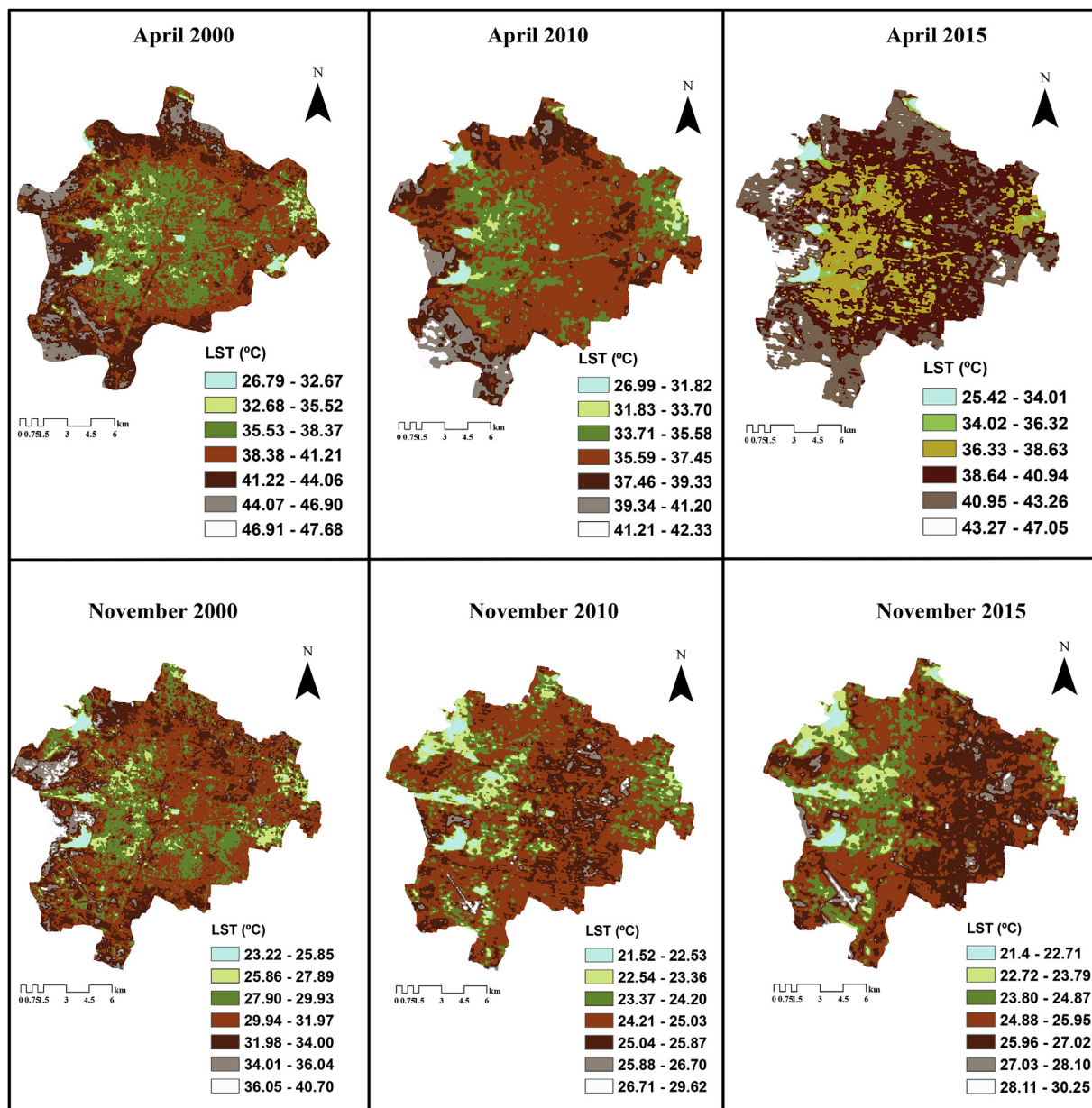


Fig. 3. LST in Nagpur city in different seasons and years.

**Table 2**  
Variation of mean LST (°C) among different LULC classes from 2000 to 2015.

LULC	LST (°C)					
	Apr-00	Apr-10	Apr-15	Nov-00	Nov-10	Nov-15
Urban built-up	38.8	39.3	39.9	24.9	25.1	25.8
Bare ground	42.18	42	40	24.7	24.8	25.7
Sparse vegetation	40.99	40.7	39.5	23.8	23.9	25.1
Waterbodies	28.47	28	29.6	22	22.05	22.2
Vegetation	38.9	38.6	36.4	24.22	24.1	24.3

**Table 3**

Changes of LST (°C) between 2000 and 2010, 2000 and 2015 and 2010 and 2015 in NMA.

LULC	2000–2010		2000–2015		2010–2015	
	Δ LULC (ha)	Δ LST (°C)	Δ LULC (ha)	LULC	Δ LULC (ha)	Δ LST (°C)
Urban built-up	2737	0.2	5416	0.9	2679	0.7
Bare ground	10	0.1	32	1	22	0.9
Sparse vegetation	–573	0.1	–2959	1.3	–2386	1.2
Waterbodies	–1749	0.05	–1951	0.2	–202	0.15
Vegetation	–425	–0.12	–538	0.08	–113	0.2

The emissivity of a surface is defined as the conversion of heat energy from an earthed object into above-surface radiation (Weng, Lu, & Schubring, 2004; Sobrino, Jiménez-Muñoz, & Paolini, 2004; Zakšek & Oštir, 2012; Bechtel, Zakšek, & Hoshyaripour, 2012; Weng & Fu, 2014; Snyder, Wan, Zhang, & Feng, 1998). Meteorological parameters included air temperature, precipitation, relative humidity, wind speed, etc. were obtained from the Indian Meteorological Department (IMD). Also, air temperature from 46 locations has been collected for validation purposes. Climate Consultant 5.3 software module has been used to visualize the meteorological parameters. Study of different spots in and around the city was done to examine the various factors responsible for thermal changes in urban areas. These spots were identified from the LST map through remote sensing. The areas were identified by temperature difference, built form conditions, and greenery within site. Data of climatic parameters like temperature, humidity, wind speed in these gathered with the help of device Lutron AH-4223, study of factors like land use, greenery within identified areas, data on typical building materials and characteristics, etc. in the identified areas was gathered to understand the impact of these factors in heat generation. 46 such spots were identified on the basis on built up and greenery in the locality.

The state-of-art of retrieval of LST has been taken from Sannigrahi et al. (2017).

The Spatio-temporal dynamics of LST has been quantified using Landsat ETM+ (band 6<sub>1</sub> and 6<sub>2</sub>, 60 m) and L8 TIRS/OLI (band 10 and band 11, 100 m) thermal data obtain from <https://earthexplorer.usgs.gov> for 2002 and 2015. The pixel digital numbers (DN) was transformed into atmospheric (TOA) radiance values as follows:

$$L_{\lambda} = G_{rescale} \cdot Q_{cal} + B_{rescale} \quad (1)$$

where  $L_{\lambda}$  is the spectral radiance,  $G_{rescale}$  and  $B_{rescale}$  are the band-specific gain and bias factors,  $Q_{cal}$  is the DN values of the thermal band.

For Landsat 8:

$$L_{\lambda} = M_L \cdot Q_{cal} + V_L \quad (2)$$

where  $M_L$  is the radiance multiplicative scaling factor,  $V_L$  is the radiance additive scaling factor (Tran et al., 2017).

The at-satellite radiance information was then converted to effective at satellite temperature as follows:

$$T_b = \frac{K_2}{\ln((K_1/L_{\lambda}) + 1)} \quad (3)$$

where  $K_1$  and  $K_2$  are the first ( $666.09 \text{ W m}^{-2} \text{ sr } \mu\text{m}$ ) and second ( $1282.7 \text{ W m}^{-2} \text{ sr } \mu\text{m}$ ) calibration constant for ETM+ thermal band. For Landsat 8,  $K_1$  and  $K_2$  are  $774.89 \text{ (W m}^{-2} \text{ sr } \mu\text{m)}$  and  $1321.08 \text{ K}$  for band 10 and  $480.89 \text{ (W m}^{-2} \text{ sr } \mu\text{m)}$  and  $1201.14 \text{ K}$  for band 11, respectively (Chander, Markham, & Helder, 2009; Sannigrahi et al., 2017).

Finally, LST was retrieved after converting the at-satellite brightness temperature (K) to surface temperature:

$$T_s = \frac{T_b}{[1 + (\lambda T_b / \rho) \ln \epsilon]} - 273.15 \quad (4)$$

where  $T_s$  is at surface temperature (°C),  $\lambda$  is the wavelength of radiance.

$$\rho = h \times (c/\sigma) \quad (5)$$

where  $\rho$  = Planck's constant ( $6.626 \times 10^{-34} \text{ Js}$ ),  $c$  = velocity of light ( $2.998 \times 10^8 \text{ m/s}^{-1}$ ),  $\sigma$  = Boltzmann constant ( $1.38 \times 10^{-23} \text{ J/K}$ ) (Weng et al., 2004).

$$\epsilon_{ETM+L8} = 0.02644P_v + 0.96356 \quad (6)$$

where  $P_v$  = fractional vegetation cover can be extracted as follows:

$$P_v = \left[ \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \right]^2 \quad (7)$$

Urban heat island intensity has been estimated using relative brightness temperature concept, proposed by Xu, Xie, and Li (2013) as follows

$$T_R = (T_I - T_A) / T_A \quad (8)$$

where  $T_R$  is the relative surface temperature,  $T_I$  is the temperature (LST) observed within the city core and  $T_A$  represents the

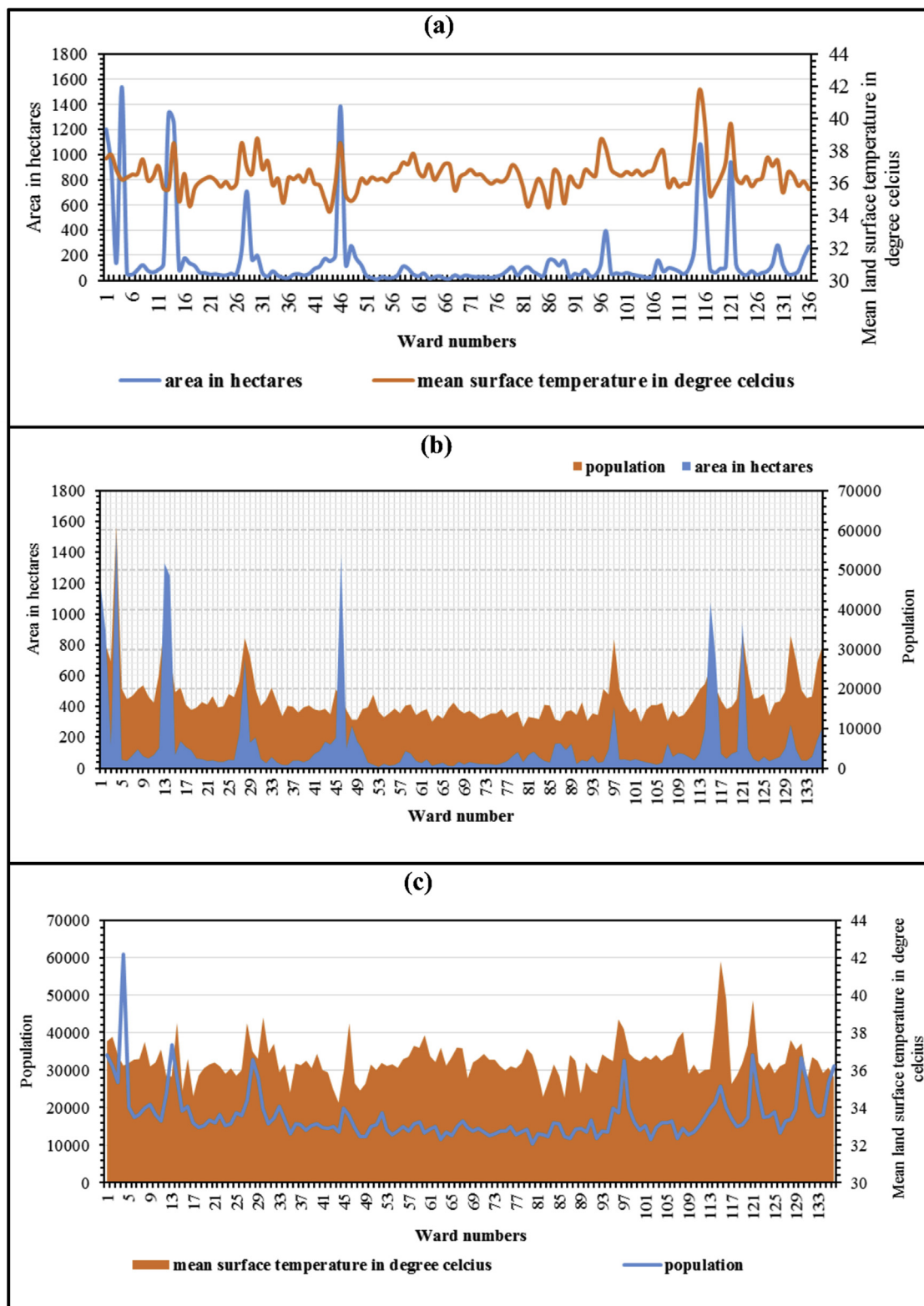


Fig. 4. Distribution of (a) Ward areas and temperature, (b) Ward wise population and area distribution and (c) Ward wise population and LST.

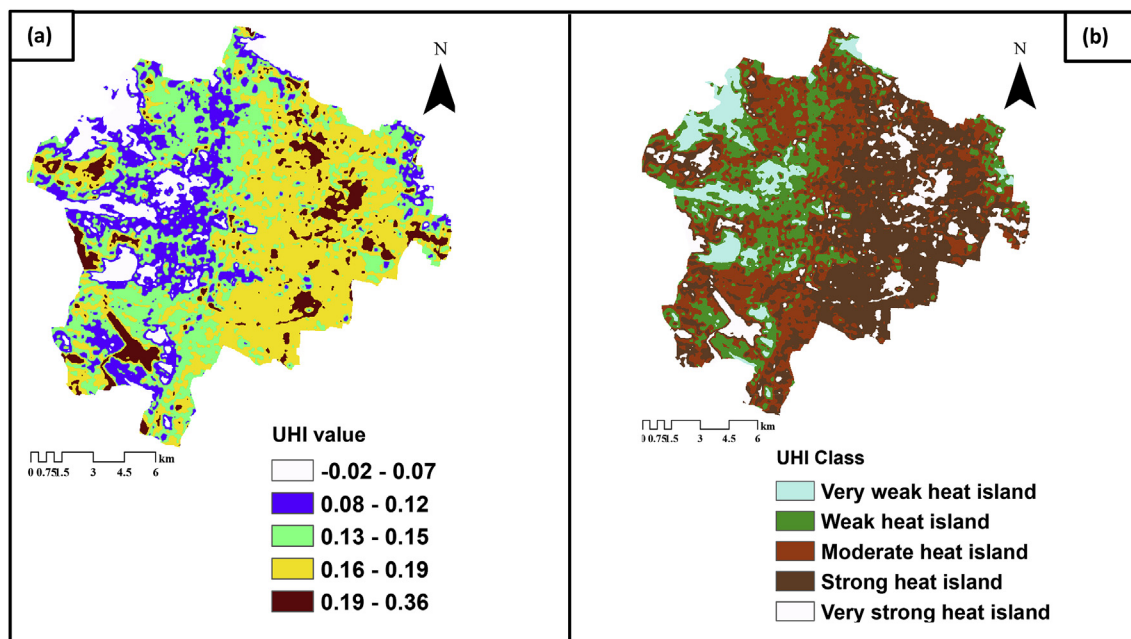


Fig. 5. UHI intensity (a) levels and (b) class in the NMA measured from satellite imagery.

temperature (LST) in the periphery region (Xu et al., 2013) (Table 1).

The biophysical composition and configuration are the key factors for addressing the thermal anomalies between rural-urban continuums. Various biophysical indices, namely Normalized Difference Vegetation Index (NDVI), Normalized Difference Built-up Index (NDBI), Normalized Difference Bareness Index (NDBaI) were incorporated in this study to evaluate the individual and collective effects of the surface green cover, urban density and bareness index on thermal response of a highly urban landscape (Sharma et al., 2015).

$$NDVI = (NIR - R/NIR + R) \quad (9)$$

$$NDBI = (MIR - NIR/MIR + NIR) \quad (10)$$

$$NDBaI = (SWIR - TIR/SWIR + TIR) \quad (11)$$

where R, NIR, SWIR, and TIR are the atmospherically corrected reflected band of red, near-infrared, shortwave infrared, and thermal infrared bands of Landsat satellite imagery (Deng & Wu, 2012).

### 3. Results and discussion

#### 3.1. Variation of air and land surface temperature across the city region

The study of climate parameters for Nagpur is shown in Fig. 2. The relative humidity is high from July to October from evening till early morning. It ranges from 20% to 40% during the harsh summer months of April and May. Humidity is low during afternoon time which makes the climate difficult to restrain. The dry bulb temperature is highest during April and May which goes beyond 38 °C. The comfort zone ranges from 20 °C to 25 °C in this region. The average annual temperature is 27–28 °C. During winter season only, i.e., from November to February the temperature ranges between 20 - 25 °C. During the rest of the year, the temperature is always above the comfort zone. The recorded low and high temperature is 7 °C and 44 °C (Fig. 2).

As urban heat island is a relative phenomenon, the mapping has been done for the entire Nagpur Metropolitan Area for understanding the difference between the rural and urban temperature. The maps were derived for different seasons in the same year for the understanding of the thermal behavior of the city adequately (Fig. 3). The high surface temperatures are shown by dark brown and gray colored areas, and cyan colored areas show the low surface temperature. This high LST cluster was mostly concentrated in the Southern, Western, and Eastern peripheral region, respectively (Fig. 3). This implies that the temperature in the city is high, also the temperature in certain areas especially in the southern side (i.e., near the airport and adjoining areas) is significantly high. The temperature is low towards the northern part of the city which may be due to the presence of green cover in Pench national park and active agricultural fields (Fig. 3). Thermal zones in the urban area can be identified from Fig. 3. As indicated in figure Fig. 3, the red-purple color exhibits the highest temperature.

The temperature is comparatively lower on the western side of the city than the eastern parts. On the other hand, some peripheral areas, however, shows a high-temperature (> 35 °C). This can be due to the development would have taken place in the peripheral





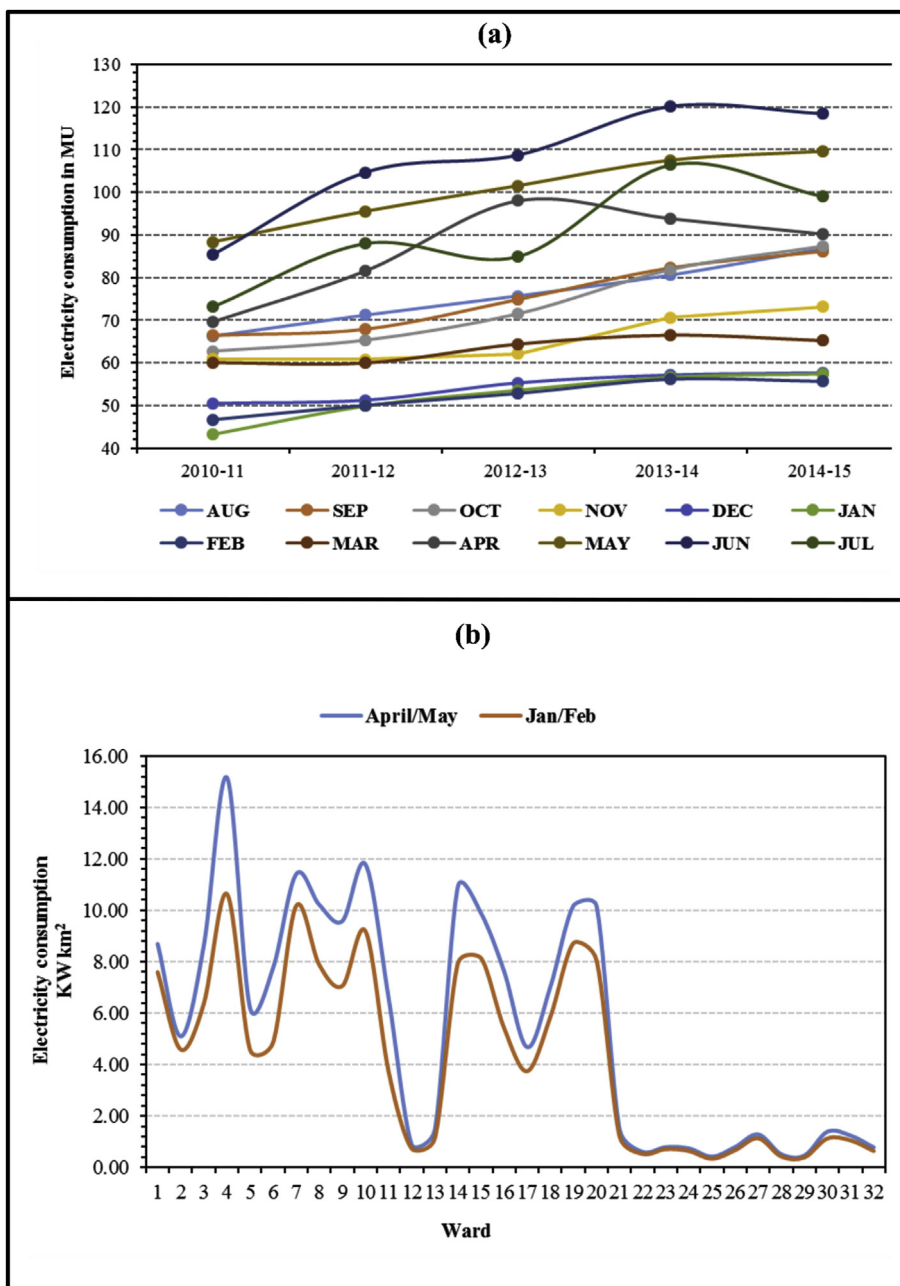


Fig. 6. (a) Showing the variations of electricity consumption of Nagpur city in different seasons and (b) area wise electricity consumption (KW km<sup>-2</sup>) in various localities around the Nagpur city.

**Table 5**  
Five different typologies of built-up and vegetation in various location of Nagpur city.

Typologies	Location
Very dense built-up areas	Mahal, Sadar, Momimpura, Tandapeth, Jaitala, New Futala, Somalwada, Vishwakarma Nagar, Dattawadi
Dense built-up areas	Sitaburdi, Gandhibagh, Dhantoli, Gorewada, Manewada, Indora, Pardi, Hanuman nagar, Khapri
Sparsely built up areas	Besa, Dhaba, Bahadura, VNIT campus, Seminary hills, Godhani, Bahadura
Moderate built-up dense areas with vegetation	Ambhjhari, Shankar nagar, Old subedhar layout, Wanjari Nagar, Nari, Pratap nagar, Narendra nagar, Rahate colony, Wardhman nagar
Moderate built-up dense areas without vegetation	Nandanvan, Reshimbagh, Takli, Nildoh, Kapsi, Manish nagar, Dighori, Jaripatka, Mankapur, Trimurti Nagar, Giripeth

areas of the city and the destruction of vegetation in this region. The temporal dynamics of the estimated LST ( $^{\circ}\text{C}$ ) are discussed in Table 2. The observed LST ( $^{\circ}\text{C}$ ) increased over urban built-up areas from 38.8 ( $^{\circ}\text{C}$ ) in April 2000 to 39.9 in April 2015, followed by water bodies, 28.47  $^{\circ}\text{C}$  to 29.6  $^{\circ}\text{C}$ , respectively. Whereas, the LST ( $^{\circ}\text{C}$ ) has been decreased over bare ground (42.2  $^{\circ}\text{C}$  to 40  $^{\circ}\text{C}$ ), followed by sparse vegetation (40.99  $^{\circ}\text{C}$  to 39.5  $^{\circ}\text{C}$ ) and vegetation cover (38.9  $^{\circ}\text{C}$  to 36.4  $^{\circ}\text{C}$ ) from April 2000 to 2015. While, in November, the estimated mean LST ( $^{\circ}\text{C}$ ) of all LULC was increased from 2000 to 2015 (Table 2). Whereas, the sensitivity between LULC and LST ( $^{\circ}\text{C}$ ) changes was analyzed and are shown in Table 3. Land-use change, especially the accelerated encroachment of urban area significantly affects the thermal behavior of an urban landscape (Feng, Zhao, Chen, & Wu, 2014; Feng et al., 2014). Ziaul & Pal, 2019 study evaluated the Discomfort Index (DI) and Physiological Equivalent Temperature (PET) in the English Bazar Municipality (India) and found that urban built-up region come across a partially uncomfortable - Cold (C) situation in winter, extremely uncomfortable situation in summer and partially uncomfortable condition in post-monsoon season both for 2010 and 2016. The findings of this study can be aligned with our observation. Gogoi et al. (2019) study on Eastern part of India had found that due to LULC changes, the mean surface temperature of the region has increased by  $\sim 0.3^{\circ}\text{C}$  during 1981–2010, while the most significant surface warming ( $\sim 0.9^{\circ}\text{C}$ ) happened during the last observation period (2001–2010). This study also found that 25–50% of this warming is connected with the changes of LULC as the spatial pattern of LULC is perfectly associated with the estimated warming of this region hence reflects a strong physical association between them. The other study such as Aithal, Chandan, and Nimish (2019), Chandra, Sharma, and Dubey (2018), Mukherjee, Joshi, and Garg (2017), Sannigrahi et al., 2017, 2018, Chakraborti et al. (2019), Singh, Kikon, and Verma (2017), Mahato and Pal (2019), Lakra and Sharma (2019), (Zhang, Odeh, & Han (2009)) etc. have conducted the study of LULC change and its effect on LST and urban heating in different Indian cities and found a strong positive association between the land conversion and increases of LST & UHI.

The mean land surface temperature is highest in the peripheral parts of the city (e.g., ward no. 115, 116, 121, 1, 2, 30) (Fig. 4). Higher population density can lead to high urban development resulting in the formation of daytime and nighttime UHI. The number of population is highest in Gandhibagh zone (wards 53 and 63). However, in the core city region (e.g. ward no 35, 36, 52, 55, 63, 66, 69, and 75), population density is very high reflecting a positive association between demographic characters of a city and LST (Sannigrahi et al., 2017, 2018). Peripheral regions show the lowest population density. The eastern part of the city is more densely populated as compared to the western part. It can be analyzed from the thermal map that the temperature is high in the eastern part of the city as compared to western which corresponds to the finding from population density analysis (Fig. 4).

It was observed that the thermal changes are more intense during the winter season. Vegetation and water bodies exhibit less temperature. The urban areas having a good proportion of vegetation mostly on the western part of the city shows lower temperature as compared to the densely built-up areas in the eastern part of the city. The high temperature is observed along the transportation corridor which is the ring road passing through the city. The peripheral areas which are mostly barren land for agriculture and surrounding the water bodies exhibit high temperature in the city (Fig. 4). This may be attributed to the very high heat absorption capacity of dark-colored basaltic rock types in these areas and also due to lack of vegetation in these regions (Bokaie et al., 2016). The use of materials in urban structures, i.e. asphalt, flooring, and concrete dismantle the surface energy balance by reducing evapotranspiration and increase sensible heat in cities are one of the main reason of day and night-time UHI experienced in a city. This could be a cause of higher temperatures in cities than outskirts (Bokaie et al., 2016). LULC results showed an increase in the urban built by 35.5% from 2000 to 2010 and 25.6% from 2010 to 2015. Waterbody increased by 2.61% and 5.61% from 2000 to 2015 owing to the increase in the rainfall and addition of Sakkardara water tank. The open land, as well as vegetation, has shown a decrease. The decrease of the vegetation has mostly been in the peripheral areas.

Thus the UHI intensity is classified into five classes as very weak heat island, weak heat island, moderate, strong and very strong heat island. The areas showing very strong heat island are indicated by white patches in Fig. 5, Table 4. The central and part of the peripheral areas (e.g., ward no 2, 3, 14, 28, 29, 30, 46, and 114) shows high temperature due to less green cover and high bare earth objects reflect more energy than water bodies and green substances. The very high heat island observed over the region (wards 6, 27, 32, and 79) due to the presence of industries and transport nagar. Regions (e.g., wards 3, 38, 39, 61, 62, 63, 72, 80, 128, and 29) have closely built urban spaces could be a reason for excess heat emission from these wards. The region comprised of ward 44 is seminary hills, protected forest area, and ward of 86 having a large green protected area, which shows a weak heat island. Furthermore, water bodies and vegetation object show very weak urban heat island intensity, observed throughout this research (Fig. 5).

The concentration of thermal heats in the urban environment resulting from the consumption of electricity. Therefore, this study also ensemble the ward-wise electricity data and its relationship with the thermal environment (Fig. 6). It shows that in domestic consumption, the pattern of electricity consumption has been increasing over the years (MSMEDCL, Govt. of India). The highest consumption is in the month of June when seasonal changes occur (Fig. 6a). The consumption is regularly increasing during the month of May which is peak during summertime (Fig. 6b). Based on the study, 5 different typologies of built-up and vegetation of various location in Nagpur city were categorized and are shown in Fig. S1, and Table 5.

### 3.2. Analysis of the biophysical parameters

The NDVI analysis in the metropolitan area shows that the vegetation is higher towards the northern part, whereas it reduces in the southern and western part (Fig. S2). Relating this to the LST in the region, it can be observed that the temperature is lower in the areas where vegetation is high (Fig. S2). Also, the NDVI changes can be seen in different seasons of the same year and also in different years. The NDVI is higher in April 2015 than in April 2000 which may be owing to the higher amount of rainfall received in April 2015 as studied from the meteorological data. High temperature can also be attributed to the bareness as a bare ground will heat up more than a vegetated ground (Bokaie et al., 2016). Fig. S2 shows that the vegetation in the city is not balanced. It is high in the

western part which maybe because of the presence of various academic institutions, botanical gardens, seminary hills, PKDV agricultural land, etc. On contrary, the eastern part is devoid of vegetation. Also, the areas in the periphery, especially near the airport and Ambajhari lake has very low vegetation. The bareness is also high in the peripheral regions (Fig. S2).

#### 4.1. Policy implementation

It is analyzed that the areas on the periphery are having barren land exhibit a high temperature. This also consists of the catchment area of Ambajhari and Gorewada Lake. The species of trees should be selected to attract biodiversity. The land capability analysis suggests that the area surrounding these water bodies have a fairly good cultivable land. Also, the soil erodible condition is high in these zones. Massive plantations should be done in these areas for temperature reduction as the impervious streets are highly prone to heat absorptions (Fig. S3). The analysis shows that open space, barren land, in general, have a high LST value, but the area can use for plantation, and children park. Therefore, active evaporation can reduce the extreme thermal characteristics of the city. On the other ways, existing parks and playgrounds in the urban area cut the UHI effects. Our analysis suggests that relevant policy and initiatives that encourage green urban development can help in reduction of the temperature in an urban area. Several places in Nagpur need to be protected in terms of their degrading vegetation coverage, agricultural land loss in the peripheral areas of the city, reducing green space in the city Centre (PKV land), hill areas-Seminary hills, Sitaburdi fort, Hazari Pahad areas, lake catchment areas-Ambajhari, and Gorewada.

From the study of open spaces analysis, it could be seen that the open spaces in the city are lacking in some areas and there is a scope for improvement in terms of vegetation in these spaces. These open spaces could be used as active evaporation areas if properly planned. Urban greenery can take place in the existing parks and playgrounds in the municipal area and that too reduce urban heating. The designated parks and playgrounds especially in areas like zone 9, areas like Budhhanagar, Vaishali Nagar, Siddhart Nagar, Nalanda Nagar, Taware Colony, belonging to wards 38,37,22,8,9; zone 8 areas like Harihar nagar in ward 58, zone 3 parks and gardens in ward 91, 126,103, zone 5 areas like Nandanvan, Nehru Nagar in ward 99,100,101 need attention in terms of increasing green cover and green city planning.

#### Conclusion

This study compiled of remote sensing satellite imageries and field survey and found that the thermal changes and urban heat island exist in Nagpur city. The urban thermal environment of Nagpur is an environmental issue leading to a need for a smart city planning with a focus on strategies for reduction in temperature that create comfortable living conditions within the area. It had seen from field survey as well as the satellite-derived land surface temperature that the factors such as less percentage of green area and high built-up density are responsible for extensive urban heating. The vegetated areas regulate the temperatures anomalies between the core city and outskirts. The temperature is comparatively lower on the western side of the city than the eastern parts. On the other hand, some peripheral areas, however, shows a high-temperature ( $> 35^{\circ}\text{C}$ ). This can be due to the development would have taken place in the peripheral areas of the city and destruction of vegetation in this region. The observed LST ( $^{\circ}\text{C}$ ) increased over urban built-up areas from  $38.8^{\circ}\text{C}$  in April 2000 to  $39.9^{\circ}\text{C}$  in April 2015, followed by water bodies,  $28.47^{\circ}\text{C}$  to  $29.6^{\circ}\text{C}$ , respectively. Whereas, the LST ( $^{\circ}\text{C}$ ) has been decreased over bare ground ( $42.2^{\circ}\text{C}$  to  $40^{\circ}\text{C}$ ), followed by sparse vegetation ( $40.99^{\circ}\text{C}$  to  $39.5^{\circ}\text{C}$ ) and vegetation cover ( $38.9^{\circ}\text{C}$  to  $36.4^{\circ}\text{C}$ ) from April 2000 to 2015. Water bodies and vegetation show very weak urban heat island intensity, which implies that the availability of these factors is essential for mitigating the thermal effects. The peripheral areas are also vulnerable to heating intensity, due to lack of green cover and increasing barren land. Although the population density is very less in these areas, heat mitigation is the priority in these areas. Research result revealed from the expert opinion survey that green areas and landscaping should be prioritized as a mitigation measure for improving the thermal environment of Nagpur. Additionally, practice like rainwater harvesting through mandatory is not thoroughly observed during this research period, for which strict laws must be made for implementation of these policies. The proposed planning approaches and findings of this study could be helpful to the planners, land administrators, and decision-makers for adopting relevant and useful land use plans, green city plan for mitigating the rising temperature and thermal discomfort of the city.

#### Acknowledgment

SS and SC acknowledges UGC for providing continuous research fellowship for carrying out the research at Indian Institute of Technology (IIT), Kharagpur (India). SJ would like to acknowledge MHRD for providing funding for the research being carried out at the Indian Institute of Technology (IIT), Kharagpur (India).

#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jum.2019.09.004>.

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