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RESEARCH PAPER

Identifying Urban Hotspots and Cold Spots in Delhi Using the Biophysical Landscape Framework

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Abstract: Urban heat islands (UHIs), which are formed by biophysical landscape transformations, have significant adverse effects on environmental quality as well as human health, resources, and facilities. Variations in UHI intensity give rise to urban hotspots (UHSs) and cold spots in different parts of the city. This study identifies such hotspots and cold spots in Delhi by classifying the city into zones of different UHI intensities using biophysical landscapes. The data on the selected biophysical landscapes were obtained from satellite images and secondary sources. The impact of different biophysical landscapes on UHI intensity was calculated using the weighted overlay method performed using ArcGIS software. The city of Delhi was thus divided into four zones, based on UHI intensity. It was found that UHSs cover about 45% of the total area and are mostly located in eastern and central Delhi. While built-up areas form the major source landscape, vegetation cover is the major sink landscape as per land surface temperature (LST) and UHI intensity. The findings of this study will help urban planners and policymakers identify UHSs and adopt suitable policies and measures to mitigate UHIs based on the different intensity zones.

Keywords: Biophysical landscape; LST; urban hotspot; Delhi

1. INTRODUCTION

The rapid rate of urbanization worldwide—particularly in developing countries—has resulted in massive changes in the biophysical landscape and thermal environment, which has led to significant changes in the land surface temperature (LST) (Liu *et al.* 2012; Traore *et al.* 2021). This has resulted in the

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formation of urban heat islands (UHIs) (Balew and Korme 2020; Ranagalage *et al.* 2019; Roberts *et al.* 2015; Simwanda *et al.* 2019). UHIs have a negative impact on the microclimate and daily weather of cities, human health and behaviour, electricity consumption, water consumption, and the use of other resources and facilities (Chan 2011; Mohan and Kandya 2015; NDMA 2016; Shi and Zhang 2018). However, the intensity and effect of UHIs are not distributed uniformly over the city, as different biophysical landscapes respond differently to heat radiation, absorption, and storage, which, in turn, influences the LST (Priyankara *et al.* 2019; Yang *et al.* 2020). This leads to the generation of urban hotspots (UHSs) wherein urban heating is highest and necessitates monitoring and planning.

The spatial pattern of UHI intensity depends on several factors including vegetation cover, availability of water bodies and open spaces, built-up areas, and the presence of industries, transportation, and other anthropogenic activities (Estoque, Murayama, and Myint 2017; Hang and Rahman 2018; Li *et al.* 2017; Traore *et al.* 2021; Vani and Prasad 2019). Therefore, the impact of the different biophysical landscapes of the city on UHI intensity and the creation of UHSs and cold spots must be studied to adopt suitable mitigation policies and to optimize the use of resources.

UHIs are areas that experience an increase in temperature as a result of anthropogenic activities such that there is a warm landmass between cool areas (a natural landscape with lower temperatures). The mixed effects of anthropogenic heat discharge, the increase in impervious surfaces, and a decline in vegetation density contribute to UHI intensity (Ali and Nitivattananon 2012; Bonafoni, Baldinelli, and Verducci 2017; Hang and Rahman 2018). The contributions of different features of the biophysical landscape to UHI intensity differ and vary over space, as they could work as either a source landscape or a sink landscape (Pramanik and Punia 2020). Source landscapes intensify the LST and the UHI effect. Some examples are built-up areas, industries, transportation facilities, air-conditioned environments (Puppala and Singh 2021), bare soil, and others (Hang and Rahman 2018; Pramanik and Punia 2020; Puppala and Singh 2021; Toy and Yilmaz 2010; Zhu *et al.* 2017). Sink landscapes decrease the LST and UHI intensity and comprise vegetation cover, water bodies, open spaces, cropland, and others (Hang and Rahman 2018; Pramanik and Punia 2020; Mathew, Khandelwal, and Kaul 2017; Sannigrahi *et al.* 2017). These factors control the intensity and impact of UHIs and their spatial variations in almost all cities around the world.

The impacts of UHIs on microclimates, environmental quality, and quality of life are so profound that the phenomenon and its relationship with natural and anthropogenic factors have been explored in numerous studies in almost all major cities in recent decades. These include Athens (Katsoulis and Theoharatos 1985), Tokyo (Saitoh, Shimada, and Hoshi 1996), Singapore and Kuala Lumpur (Tso 1996), Shanghai (Chow 1992), Washington, DC (Kim 1992), London (Jones and Lister 2009), Dhaka (Molla *et al.* 2014), Faisalabad (Shabana, Bashir, and Ali 2015), and Bangkok (Ali, Pumijumnong, and Cui 2018). In India, the number of studies dealing with the thermal environments of cities and their relationships with various biophysical factors has increased during the past decade (Chakraborty, Kant, and Mitra 2015; Gupta and Parashar 2020; Hang and Rahman 2018; Mallick, Rahman, and Singh 2013; Mathew *et al.* 2016; Pandey *et al.* 2012; Pramanik and Punia 2020; Sannigrahi *et al.* 2018). These cities include Jaipur (Gupta 2012; Mathew, Khandelwal, and Kaul 2017), Greater Hyderabad (Sannigrahi *et al.* 2018), Vijayawada (Puppala and Singh 2021), Guwahati (Borbora and Das 2014), Lucknow (Singh, Kikon, and Verma 2017), Bhubaneshwar (Swain *et al.* 2017), Ahmedabad (Mathew *et al.* 2016), and Delhi NCR (Gupta and Parashar 2020; Hang and Rahman 2018; Kant *et al.* 2009; Mallick, Kant, and Bharath 2008; Mallick and Rahman 2012; Mohan and Kandya 2015; Pramanik and Punia 2020; Sharma and Joshi 2014, 2013).

Most of these studies examine the correlation between LST and different aspects of land use, land cover, and spatial patterns of UHIs (Hang and Rahman 2018). Only a few studies classify Indian cities into different UHI zones based on the biophysical landscape (Gupta 2020, 2012; Pramanik and Punia 2020). Gupta (2012) analyses the spatial pattern of UHIs in Jaipur and classifies the city into four UHI zones based on vegetation cover, built-up area, population density, industry, traffic congestion, and LST. Pramanik and Punia (2020) examine the impact of land cover and land use changes on the LST and UHIs and their district-wise and sub-district-wise distribution over Delhi. However, the district-wise and sub-district-wise classification of UHI intensity does not give a clear picture of the distribution and location of UHSs, which is required to draft effective and efficient policies for the mitigation of UHI intensity and associated changes in the biophysical landscape.

Analysis of satellite imagery through the assimilation of geographic information system (GIS) and remote sensing techniques helps scholars calculate the correlation between the biophysical landscape and UHIs and their spatial patterns (Gupta 2012; Hang and Rahman 2018; Mallick, Rahman, and Singh 2013; Mathew *et al.* 2016; Pandey *et al.* 2012; Pramanik and Punia 2020; Sannigrahi *et al.* 2017). Remote sensing and the GIS technique are suitable for mapping, monitoring, and measuring the LST and UHI intensity over a large area (Gluch, Quattrochi, and Luvall 2005). With the help of satellite imagery, we can obtain the spatial pattern of the LST, which can be used to examine the UHI intensity and associated factors (Puppala and Singh 2021).

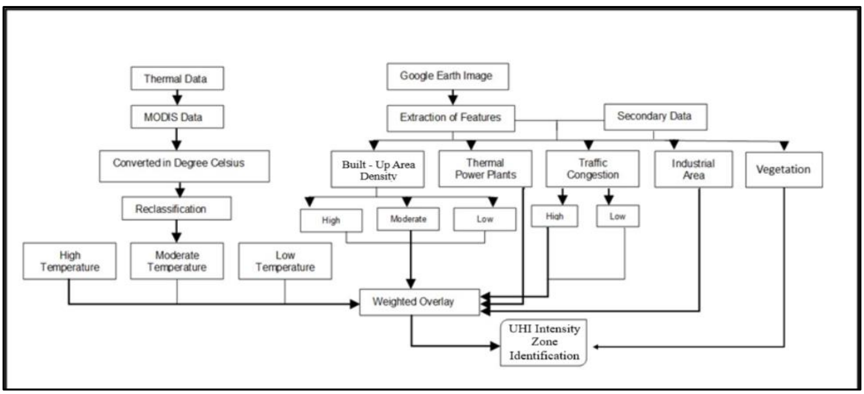
This study classifies the city of Delhi into different UHI zones, identifies UHSs, and discovers their association with different features of the biophysical landscape comprising built-up areas, industries, thermal power plants, traffic congestion, vegetation cover, and LST using satellite imagery and the GIS technique.

2. MATERIAL AND METHODS

2.1. Study Area

Delhi is the second-largest megacity in the world and one of the fastest-growing cities in India, with about 17 million people residing in an area of 1,483 sq km. It is situated between 28°24'17" N and 28°53'00" N and longitudes 76°45'30" E and 77°21'30" E.. The altitude of the city ranges between 213 m and 290 m. The city is largely a plain area except for two main relief features—the Delhi Ridge and the Yamuna River—which act as cooling agents and thermal moderators for the climate. It has an extreme continental-type climate where the annual temperature varies between 3°C and 45°C and the average annual rainfall ranges from 400 mm to 600 mm. Thorny scrub-type vegetation—typical of semi-arid environments—covers about 20% of Delhi. The population of the city grew from 1.7 million in 1901 to 17 million in 2011 (Census of India 2011). The rapid increase in urbanization has accelerated the landscape transformation of Delhi from a mainly rural area to an urban area, which has influenced the thermal environment of the city.

Figure 1: Methodology for Identification of UHI Intensity Zones in Delhi



Source: Prepared by the author

2.2. Database and Methods

The data was collected from satellite maps and other secondary sources. The data on LST, obtained from MODIS (MOD11A1) satellite data for March 2020, was converted to degrees Celsius. Google Earth data from March 2020 was used to extract the selected landscape features—comprising built-up areas, industries, thermal power plants, areas with traffic congestion, and vegetation cover—which were verified through data collected from secondary sources. The weighted overlay method was used to identify UHI intensity zones, UHSs, and urban cold spots, as shown in Figure 1.

2.3. Estimation of LST

LST was used as the reference to classify the city into different UHI intensity zones. The data on LST was extracted from the analysis of MODIS satellite imagery. The computation of LST from satellite images has been described extensively in the literature and involves three steps. First, the top-of-atmosphere (TOA) reflectance values are obtained by converting the digital numbers (the brightness value of a pixel) of the thermal infrared bands using Equation 1:

$$L_\lambda = ML \times DN + AL \tag{1}$$

where L_λ denotes the TOA radiance, *ML* refers to the multiplicative rescaling factor of a particular band, *DN* represents the standard values of pixels, and *AL* is the additive rescaling factor for the specific band. Next, the brightness temperature is calculated using the TOA reflectance of each pixel, using Equation 2:

$$T = K_2 \ln ((K_1/L_\lambda) + 1) \tag{2}$$

where T represents the brightness temperature measured in Celsius, L_λ is the TOA reflectance, and K_1 and K_2 represent the constants for thermal conversions of the specific band. Finally, the LST is corrected for the emissivity of different urban landscapes using Equation 3:

$$\text{LST} = T/1 + (\lambda T/p) \ln \varepsilon \tag{3}$$

where λ is the wavelength at the centre of the thermal infrared band and ε is the emissivity.

2.4. Computation of Normalized Differential Vegetation Index (NDVI)

Normalized differential vegetation index (NDVI) is a graphical indicator of the quantity of green biomass, which is estimated to identify the impact of vegetation on temperature; as the vegetation index increases, the LST decreases. The vegetation index was calculated using the red and near-infrared bands of Landsat-8 imagery, which helps in monitoring vegetation cover. NDVI is calculated using Equation 4:

$$\text{NDVI} = (NIR - RED)/(NIR + RED) \tag{4}$$

where RED and NIR represent the reflectance in the red band and near-infrared band, respectively. The NDVI varies between +1 and −1, which represent the highest and lowest greenness, respectively.

2.5. Identification of UHI Intensity Zones and UHSs

Weights were assigned to each selected landscape feature based on its impact on UHI intensity, as described in Table 1. Several parameters have been incorporated for the analysis of UHIs using the multi-criteria analysis method. The built-up area is one of the most important factors in heat island phenomena in cities (Han *et al.* 2022; Choi, Suh, and Park 2014; Oke 1982; Gupta 2012; Khandelwal, Goyal, and Kaul 2010; Saaroni *et al.* 2000). Accordingly, it has been assigned the highest weightage (30%) under a three-point Likert Scale based on density (high, moderate, or low). LST estimation is very useful in determining the UHI (Bokaie *et al.* 2016; Schwarz, Lautenbach, and Seppelt 2011; Sundarakumar 2012). It was grouped as per the three-point Likert Scale and was given a weightage of 25%.

Next, the presence of industries and thermal power plants (Gupta 2012; Gao *et al.* 2022; Phelan *et al.* 2015; Zhang *et al.* 2017) was marked on a two-point Likert Scale, with 20% and 15% weightage, respectively. Finally, traffic congestion, which has a significant effect on UHI intensity (Zhu *et al.* 2017; Husni *et al.* 2022; Louiza, Zeroual, and Djamel 2015), was also classified as high or low using a two-point Likert Scale. The UHI intensity zones and the UHSs and cold spots were identified by overlaying each biophysical landscape in the ArcGIS using the LST map as the base.

3. RESULTS AND DISCUSSION

3.1. Spatial Pattern of LST

The areas with the maximum number of LST pixels were found inside the city, and those with the minimum number of LST pixels were found on the fringe or northwest and southwest boundaries of the fringe area, as shown in Figure 2. The data shows that the LST in different parts of the city varied between 27°C and 35°C—a difference of 8°C between UHSs and cold spots—in March 2020. Thus, the maximum LST occurred in the core of the city, which has the largest impervious area and the lowest vegetation cover. In contrast, the LST was low in the northwest and southwest boundaries of the study area, where the impervious area is low and vegetation cover is high.

Table 1: Weightages of Different Biophysical Landscapes Responsible for UHI Intensity

Parameters	Sub-parameter	Scale Value	Impact (%)
Density of built-up area	High	5	30
	Moderate	3	
	Low	1	
Land surface temperature	High	5	25
	Moderate	3	
	Low	1	
Major industries	Yes	5	20
	No	1	
Thermal power plants	Yes	5	15
	No	1	
Traffic congestion	High	5	10
	Low	1	

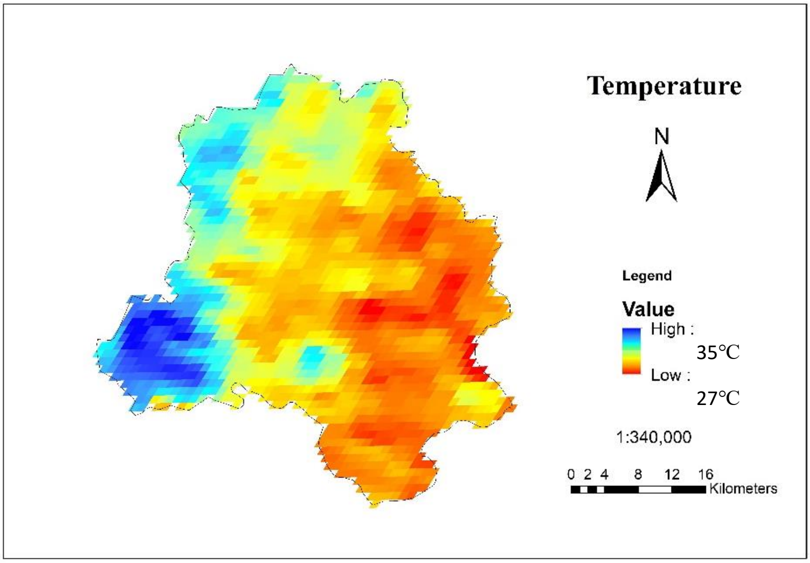
Source*:* Multi-criteria analysis method (Gupta 2012; Mirzaei and Haghighat 2010)

3.2. Spatial Distribution of Vegetation Cover

Vegetation cover is a major sink landscape feature that helps in minimizing the LST and UHI intensity. Hence, the NDVI of Delhi was estimated using Equation 4 for four months—December, March, June, and September—across four different seasons in the period 2019–2020, as shown in Figure 3. The results indicate that Delhi witnessed a seasonal variation in the vegetation cover. In December, the NDVI for the city varied from −0.092 to 0.45. In March, the NDVI ranged between 0.21 and 0.74, after which it showed a decline in June and September. The seasonal variation in the NDVI in the city may be attributed to the presence of clouds and fog, as a value of NDVI below 0 indicates the presence of clouds and snow. Therefore, calculating NDVI in March would give the best results for vegetation cover due to the lack of clouds and fog in the city.

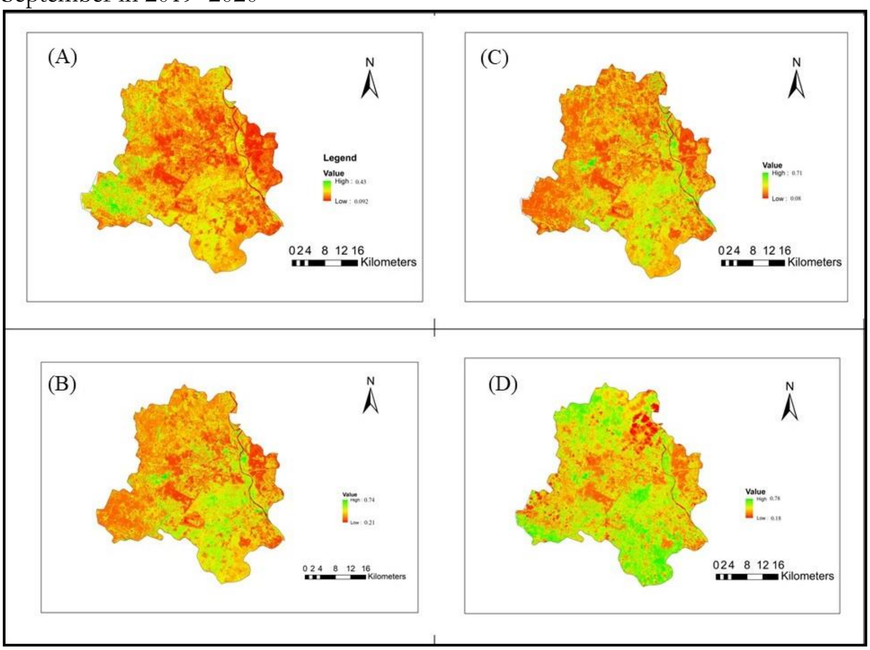
The NDVI maps help us understand vegetation patterns in the city and show that there was healthy vegetation where the UHI intensity was low and built-up areas where the intensity was high. The spatial pattern of vegetation cover shows that the central part of the city was devoid of vegetation except for a few patches of green. Most of the vegetation was found along the Yamuna bank and in the western and eastern outskirts of the city. The pattern of vegetation cover in the city highlights the impact of built-up areas because the areas devoid of vegetation cover were those with a high built-up area density.

Figure 2: Land Surface Temperature in Delhi



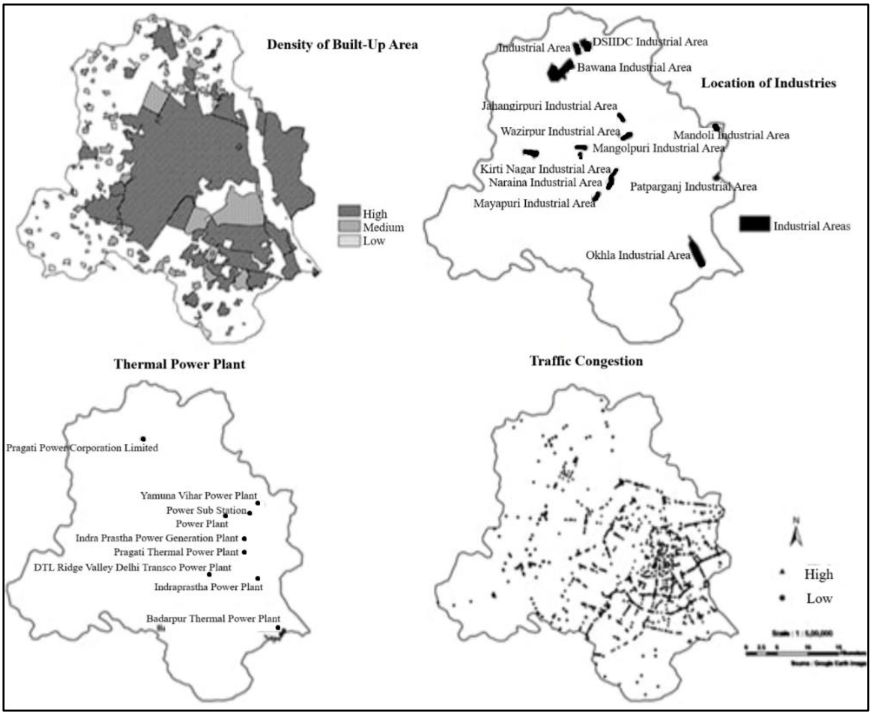
Source: Prepared by the author using MODIS data

Figure 3: NDVI Images of Delhi for (A) December, (B) March, (C) June, and (D) September in 2019–2020



Source: Prepared by the author using open source satellite data

Figure 4: Built-up Area–Density, Industries, Thermal Power Plants, and Traffic Congestion in Delhi



Source: Prepared by the author using Google Earth data

3.3. Spatial Pattern of the Source Landscape

The source landscapes included in the study were built-up areas, industrial areas, and areas with thermal power plants and traffic congestion, as shown in Figure 4. As per the literature, these are the major contributors to LST and UHI intensity, as these landscapes have different heat absorption, reflection, and storage properties. Some of these landscapes, such as industries and transportation, also release air pollutants and particulate matter into the atmosphere, which trap short-wave terrestrial radiation, further increasing the LST and intensifying the UHI effect. The density of built-up areas is the most important determinant of UHI intensity.

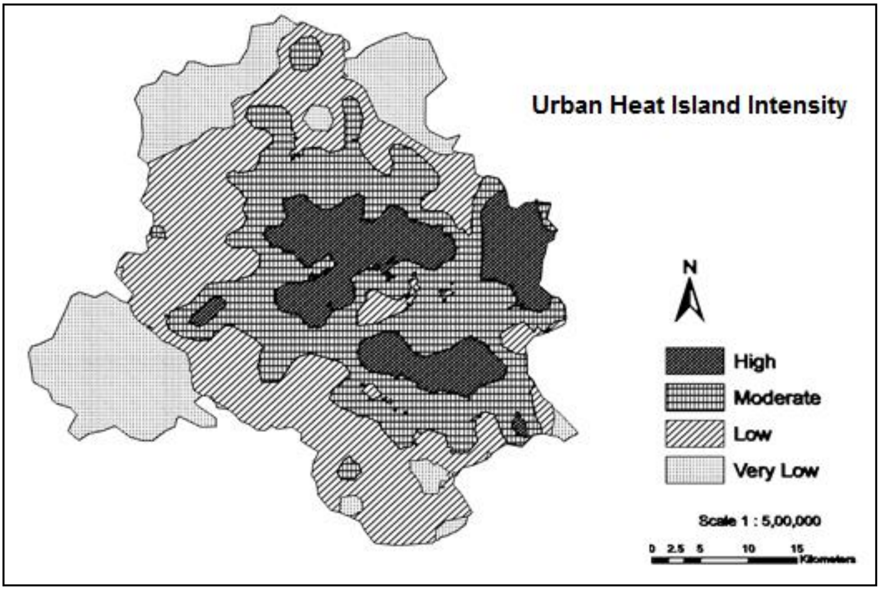
The findings of this study indicate that there was a high density of built-up areas in the central, eastern, and south-eastern parts of the city. There were also some patches with a high density of built-up areas in the northern and western parts of the city. Most of the industries were located in the northern, eastern, and central parts of the city. The thermal power stations were mostly located in the eastern part of the city where traffic congestion was also high.

3.4. UHI Intensity Zones and Location of Urban Hotspots and Cold Spots

The weighted overlaying of different biophysical landscape features in the ArcGIS classified the city into four UHI intensity zones—high, medium, low, and very-low-intensity zones—as shown in Figure 5. While the areas with high and moderate UHI intensity are termed UHSs, the areas with low and very low intensity are considered cold spots. UHSs covered about 45% of the area of the city, and the rest of the areas were cold spots. UHSs were mostly located in the areas around the central and eastern parts of the city, but a few small pockets were also located in the northern, western, and southern parts of the city. Urban cold spots were mostly found in the outskirts of the city, with some pockets also located in hotspot zones. The high UHI intensity zone covered almost 15% of the area, including the localities of Kashmiri Gate, Kamla Nagar, Wazirpur, Lajpat Nagar, Greater Kailash, Badarpur, Patparganj, Anand Vihar, Dilshad Garden, and Shahdara, as displayed in Table 2. The moderate UHI intensity zone covered about 30% of the area and included localities such as New Delhi, Shakarpur, Laxmi Nagar, Nawada, Kirari, Rohini, Jahangirpuri, Shalimar Bagh, and others.

The low UHI intensity zone covered an area of about 34% and was mostly located on the outskirts of the city. However, some patches of low UHI intensity were also found in central and north Delhi, which may be due to the presence of open spaces and vegetation cover. The UHI intensity of the areas located in the vicinity of the Yamuna River was usually low because of the presence of a relatively larger area under scrub vegetation as well as open spaces. The Yamuna, apart from the monsoon months, does not have much water due to a number of anthropogenic causes such as pollution, discharge of effluents, and so on. Therefore, it does not play a critical role in ameliorating heat islands in Delhi. Moreover, Delhi sits astride the Yamuna, that is, only the north-eastern part of Delhi can be influenced by the river. Thus, it does not play a prominent part in modifying the LSTs of the whole of Delhi. The localities of Delhi with low UHI intensity included Kakrola, DDA Colony, Sainik Farm, Rangpuri, and others, as shown in Table 2. The remaining areas came under the very low intensity zone and included the localities that lie outside the city, covering only about 21% of the area of the city.

Figure 5: Urban Heat Island Intensity Zones in Delhi



Source: Compiled by the author using GIS tools

Table 2: Areas and Localities of Delhi under Different UHI Intensity Zones

UHI Intensity Zone	Area (sq km)	Area (%)	Names of Localities of Delhi
High	222.5	15.0	IP Extension, Patparganj, Shahdara, Sarojini Nagar, Dilshad Garden, Greater Kailash, Kamla Nagar, Badarpur, Kashmiri Gate, Janakpuri, Tis Hazari, Tilak Nagar, Paschim Vihar, Punjabi Bagh, Mangolpuri, Azadpur, Wazirpur, Lajpat Nagar, Naraina, Sarai Rohilla
Moderate	440.5	30.0	Sunder Nagri, New Mandoli, Shakarpur, Yamuna Bank, Laxmi Nagar, Indraprastha, Bindapur, New Delhi, Nawada, Rohini, Kirari Suleman Nagar, Shalimar Bagh, Narela, Nathupura, Bawana, Jahangirpuri, Samaypur
Low	504.0	34.0	Gopal Nagar Extension I, Kakrola, Kanjhawala, Shahpur Garhi, DDA Colony, Shampur Khampur, Todapur, Mayur Vihar I Extension, JJ Colony, Mayur Vihar Phase II, Tughlakabad Extension, Fatehpur Beri, Sainik Farm, Rangpuri

UHI Intensity Zone	Area (sq km)	Area (%)	Names of Localities of Delhi
Very low	318.0	21.0	Jaffarpur Kalan, Badarpur Majra, Nangal Thakran, Fatehpur Jat, Barwala, outskirt croplands
Total	1,484.86	100	

Source: Compiled by the Author using GIS Tools

The spatial pattern of UHI intensity and location of hotspots and cold spots reveal that built-up area density, industrialization, vegetation cover, open spaces, and traffic congestion determine UHI intensity. However, findings reveal that built-up area density and vegetation cover are the major determinants of UHI intensity, which is similar to the findings of earlier studies (Pramanik and Punia 2020; Puppala and Singh 2021; Sannigrahi *et al.* 2017). While built-up area is the major source landscape of UHI intensity, vegetation cover works as the major sink landscape for the same. The impact of industries, thermal power plants, and traffic congestion on UHI intensity is minor, but they play a crucial role in increasing the intensity of UHIs in built-up areas, as they hinder free air circulation.

4. CONCLUSION

This study aimed to identify UHI intensity zones in the city of Delhi by analysing the impact of different biophysical factors. The factors employed in the study for the identification of UHI intensity zones included LST, vegetation, density of residential and commercial buildings, location of industries and thermal power plants, and traffic congestion. A strong correlation between built-up area density and UHI intensity was found, as most of the hotspots featured dense built-up areas. Similarly, vegetation cover had a positive impact on the UHI intensity, as most of the hotspots and cold spots were in areas where vegetation cover was sparse and high, respectively. Therefore, increasing the density of vegetation cover with the help of plants, green walls, and rooftop vegetation is an effective solution to minimize the impact of UHI intensity. Besides the density of built-up areas and vegetation cover, industries, thermal power plants, and traffic congestion also influence UHI intensity by releasing heat and pollutants into the surroundings, which helps trap heat in the terrestrial atmosphere, thus increasing the LST. Therefore, urban planners should formulate policies targeted at reducing the impact of air pollution and traffic congestion.

This study includes only a few biophysical landscapes responsible for UHIs, which is one of its limitations. UHI intensity is also influenced by wind speed, humidity, the width and angle of streets, and so on. Therefore, future studies could include all source and sink urban landscapes while demarcating UHI intensity zones and their impact on the location of hotspots and cold spots.

We conclude with the suggestion that policymakers should focus on measures to diminish the contribution of built-up areas to UHIs by using suitable materials, providing unpaved surfaces, and improving vegetation cover with the help of plants, green walls, green rooftops, and other suitable measures.

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Ethics Statement: I hereby confirm that this study complies with requirements of ethical approvals from the institutional ethics committee for the conduct of this research.

Data Availability statement: The data used to support this research is available in a repository and the hyperlinks and persistent identifiers (e.g. DOI or accession number) are stated in the paper.

Conflict of Interest Statement: No potential conflict of interest was reported by the author.

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