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Impact of Growth and Development of Built-Up Area on Land Surface Temperature and Vegetation Cover

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Abstract —Urbanization has become one of the most influential processes shaping the environmental and spatial structure of modern cities. Rapid expansion of built-up areas often occurs at the cost of natural vegetation, leading to rising surface temperatures and the intensification of Urban Heat Island (UHI) effects. The present study examines the relationship between urban growth, vegetation change, and thermal variation in Prayagraj during the period 2000–2020 using geospatial techniques and satellite-based indices. The study employs the Normalized Difference Built-up Index (NDBI) to analyse urban expansion, the Normalized Difference Vegetation Index (NDVI) to assess vegetation cover, and Land Surface Temperature (LST) to evaluate thermal conditions across eight administrative zones of the city. Multi-temporal Landsat satellite imagery and GIS-based spatial analysis were utilized to investigate temporal and spatial transformations in the urban landscape.

The findings reveal a substantial increase in built-up areas from 66.69 sq. km in 2000 to 197.81 sq. km in 2020, indicating rapid urban expansion across the city. In contrast, vegetation cover declined sharply from 199.69 sq. km to 56.72 sq. km during the same period, reflecting continuous pressure on green spaces due to urban development. Simultaneously, mean Land Surface Temperature increased significantly in all zones, demonstrating the thermal impacts of expanding impervious surfaces and declining vegetation. The study establishes a strong positive relationship between NDBI and LST, while NDVI exhibits a significant negative relationship with LST, indicating the crucial role of vegetation in regulating urban temperature. Peripheral zones, particularly Zones 5, 6, 7, and 8, recorded the highest rates of urban expansion, vegetation loss, and thermal stress, highlighting their emergence as major urban growth corridors.

The study underscores the environmental consequences of uncontrolled urbanization and emphasizes the urgent need for sustainable urban planning, ecological conservation, and green infrastructure development to reduce thermal stress and promote environmental sustainability in rapidly growing Indian cities.

Keywords: Urbanization, NDBI, NDVI, Land Surface Temperature, Urban Heat Island, Prayagraj, Remote Sensing, GIS, Built-up Area, Vegetation Cover.

I. INTRODUCTION

Urbanization represents a continuous and complex process of spatial transformation that reshapes the physical, ecological, and socio-economic structure of urban landscapes. Rapid urban growth often leads to the conversion of agricultural land, natural vegetation, wetlands, and open spaces into impervious built-up surfaces such as residential areas, transportation networks, commercial establishments, and industrial infrastructure. These transformations significantly modify the urban environment by altering land surface characteristics, hydrological processes, energy balance, and local climatic conditions, thereby affecting ecological sustainability and human well-being (Oke, 1982; Seto, Güneralp & Hutyra, 2012).

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Prayagraj, formerly known as Allahabad, is one of the oldest historical and administrative cities of northern India, situated at the confluence of the Ganga River, Yamuna River, and the mythical Saraswati River. Over the last two decades, the city has experienced rapid population growth, infrastructural development, and spatial expansion driven by increasing urbanization and economic activities. The continuous growth of residential colonies, transportation corridors, commercial centres, and institutional infrastructure has substantially transformed the land use and land cover (LULC) pattern of the city. This expansion has resulted in the decline of vegetation cover and open land, leading to considerable environmental changes within the urban ecosystem.

One of the most significant consequences of rapid urbanization is the intensification of the Urban Heat Island (UHI) effect, a phenomenon in which urban areas exhibit higher temperatures than their surrounding rural regions due to the concentration of impervious surfaces and anthropogenic activities (Oke, 1987). The replacement of natural vegetation with concrete and asphalt surfaces increases heat absorption and reduces evapotranspiration, thereby contributing to rising land surface temperatures (LST). In cities such as Prayagraj, increasing thermal stress associated with urban expansion has become a major environmental concern affecting urban climate, energy consumption, ecological balance, and public health.

In recent decades, Remote Sensing (RS) and Geographic Information System (GIS) technologies have emerged as powerful tools for monitoring urban growth and assessing environmental changes at different spatial and temporal scales. Multi-temporal satellite imagery enables the analysis of urban expansion, vegetation dynamics, and thermal characteristics with greater accuracy and efficiency (Weng, 2001). Various satellite-derived spectral indices have been extensively applied in urban environmental studies, including the Normalized Difference Built-up Index (NDBI) for identifying built-up areas, the Normalized Difference Vegetation Index (NDVI) for assessing vegetation health and density, and Land Surface Temperature (LST) for examining urban thermal conditions. These geospatial indicators provide valuable insights into the interaction between urbanization, vegetation degradation, and thermal variations across urban landscapes.

Against this backdrop, the present study examines the spatio-temporal relationship between built-up expansion, vegetation dynamics, and land surface temperature variation in Prayagraj during the period 2000–2020. By integrating satellite-based remote sensing data with GIS-based spatial analysis techniques, the study aims to evaluate the impact of rapid urbanization on the urban environment and to understand how changes in land use and vegetation cover have contributed to increasing thermal stress within the city. The findings of the study are expected to support sustainable urban planning, environmental management, and climate-resilient development strategies for rapidly growing cities.

II. OBJECTIVE

The present study seeks to investigate the spatio-temporal patterns of urban expansion and their associated environmental impacts in Prayagraj through the application of remote sensing and geospatial techniques. The study aims to analyse the growth, intensity, and spatial distribution of built-up areas using the Normalized Difference Built-up Index (NDBI), while simultaneously examining the transformation of vegetation cover through the Normalized Difference Vegetation Index (NDVI). In order to understand the thermal response of changing land use patterns, the study further evaluates variations in Land Surface Temperature (LST) across different temporal periods. By establishing the interrelationship among NDBI, NDVI, and LST, the research attempts to scientifically interpret how increasing urbanization influences ecological balance, vegetation health, and urban thermal conditions. Furthermore, the study endeavours to assess the broader environmental implications of rapid urban growth in Prayagraj city, particularly in the context of declining green spaces, rising surface temperatures, and the changing urban landscape that directly affects environmental sustainability and human well-being.

III. STUDY AREA

Prayagraj is one of the prominent urban centres of northern India, situated in the state of Uttar Pradesh. Over the last two decades, the city has witnessed rapid population growth and significant spatial expansion, resulting in noticeable transformations in its urban landscape. For the purpose of systematic analysis, the study area has been categorized into eight administrative zones, each reflecting distinct characteristics in terms of urban development, vegetation distribution, and thermal variability. The outer and peripheral zones, particularly Zones 5, 6, 7, and 8, have experienced accelerated urban growth owing to the expansion of residential neighbourhoods, transportation networks, and commercial activities. These emerging growth corridors highlight the ongoing process of urbanization and its influence on the environmental and spatial structure of the city.

IV. DATA AND METHODOLOGY

The present study is based on multi-temporal Landsat satellite imagery acquired for the years 2000, 2010, and 2020 to analyse the changing urban and environmental conditions of Prayagraj. Remote Sensing (RS) and Geographic Information System (GIS) techniques were employed for image processing, spatial mapping, and the analysis of land surface characteristics. Landsat 5 Thematic Mapper (TM) datasets were utilized for the years 2000 and 2010, whereas Landsat 8 Operational Land Imager/Thermal Infrared Sensor (OLI/TIRS) imagery was used for the year 2020 due to its improved spectral and radiometric resolution. The satellite datasets were obtained from the USGS Earth Explorer platform. Standard pre-processing procedures, including geometric correction, radiometric calibration, atmospheric correction, image mosaicking, and layer stacking, were carried out to ensure temporal consistency and analytical accuracy (Jensen, 2015; Lillesand, Kiefer & Chipman, 2015).

IV.I. NORMALIZED DIFFERENCE BUILT-UP INDEX (NDBI)

The Normalized Difference Built-up Index (NDBI) was used to identify and quantify the spatial expansion of built-up and urbanized areas within the study region. The index was developed by Zha et al. (2003) and is widely used for urban growth analysis using satellite imagery. NDBI was calculated using the Short Wave Infrared (SWIR) and Near Infrared (NIR) spectral bands of Landsat imagery through the following equation:

$$NDBI = \{SWIR - NIR\}/\{SWIR + NIR\}$$

Positive NDBI values generally indicate impervious built-up surfaces and urban areas, whereas negative values represent vegetation cover and water bodies. Landsat 5 TM imagery was utilized for the years 2000 and 2010, while Landsat 8 OLI imagery was used for 2020 to examine the pattern, intensity, and spatial extent of urban expansion across the city.

IV.II. NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI)

The Normalized Difference Vegetation Index (NDVI) was employed to assess vegetation density, health, and spatial distribution within the urban landscape. NDVI is one of the most commonly used vegetation indices in remote sensing studies and provides valuable information regarding vegetation vigour and biomass (Rouse et al., 1974). The index was calculated using the Near Infrared (NIR) and Red spectral bands according to the following formula:

$$NDVI = \{NIR - Red\}\{NIR + Red\}$$

Higher NDVI values indicate dense and healthy vegetation cover, while lower or negative values signify sparse vegetation, barren land, water bodies, or built-up surfaces. Landsat 5 TM imagery was used for the years 2000 and 2010, whereas Landsat 8 OLI imagery was applied for the year 2020 to evaluate temporal changes in urban vegetation cover.

IV.III. LAND SURFACE TEMPERATURE (LST)

Land Surface Temperature (LST) analysis was carried out to understand the spatial variation of surface temperature and its relationship with urban expansion and vegetation loss. LST is considered an important indicator for examining urban thermal environments and Urban Heat Island (UHI) effects (Weng, Lu & Schubring, 2004). The LST values were derived from the thermal infrared bands of Landsat imagery through a sequence of radiometric calibration, spectral radiance conversion, brightness temperature estimation, and land surface emissivity correction procedures.

For the years 2000 and 2010, Landsat 5 TM thermal infrared datasets were utilized, while Landsat 8 TIRS thermal imagery was employed for the year 2020. The derived LST maps enabled the identification of urban thermal hotspots and facilitated the analysis of the influence of built-up expansion and vegetation reduction on the thermal environment of the city. The integration of NDBI, NDVI, and LST analyses provided a comprehensive understanding of the relationship between urbanization, vegetation dynamics, and surface temperature variation in the study area.

V. RESULT AND FINDINGS

V.I. ZONE-WISE ANALYSIS OF NORMALIZED DIFFERENCE BUILT-UP INDEX (NDBI)

The zone-wise NDBI analysis is presented below for all eight administrative zones of Prayagraj city, comparing built-up area extent and spatial concentration for the years 2000, 2010, and 2020. The data are summarized in Table 1.

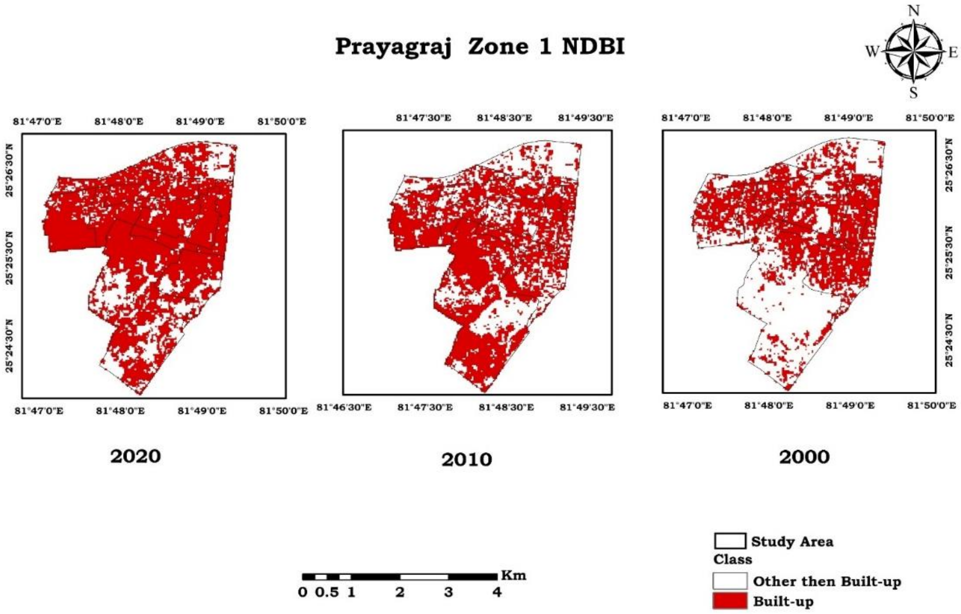
V.I.I. ZONE 1

The Normalized Difference Built-up Index (NDBI) maps for Zone 1 reveal a consistent and progressive intensification of built-up cover across all three study years. In 2000, the total built-up area of Zone 1 was recorded at 5.76 sq. km, representing 8.64% of the city's total built-up extent of 66.69 sq. km. The spatial distribution of high NDBI values was concentrated predominantly in the northern and eastern regions of the zone, where established residential and commercial wards were already in evidence, while the southern periphery—characterized by ward number 82 (Karailabagh) and its relatively higher vegetation density—displayed comparatively lower built-up intensity.

By 2010, the total built-up area of Prayagraj as a whole had expanded dramatically to 130.75 sq. km, representing a growth of approximately 96.05% over the decade. Zone 1's contribution rose from 5.76 sq. km to 7.61 sq. km, though its proportional share of the city's built-up area declined to 5.82%, reflecting the even more rapid growth occurring in peripheral zones. Notably, the previously open southern sector of Zone 1 now exhibited elevated NDBI values, indicating infilling of previously sparse areas. Ward number 28 (Jhoolelal Nagar), however, continued to record relatively lower built-up densities during this period.

In 2020, the built-up area of Zone 1 further increased to 9.00 sq. km, though its proportional contribution declined to 4.54% as the city's total built-up extent reached 197.81 sq. km—an increase of 51.28% over 2010. The central wards (71, 99, 91) of Zone 1 recorded particularly marked increases in built-up density, attributable to intensified residential construction and commercial development driven by population pressure and proximity to

Figure 1: Spatial Distribution of Normalised Difference Built-up Index (NDBI) in Zone 1 of Prayagraj City for the Years 2000, 2010and 2020



Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

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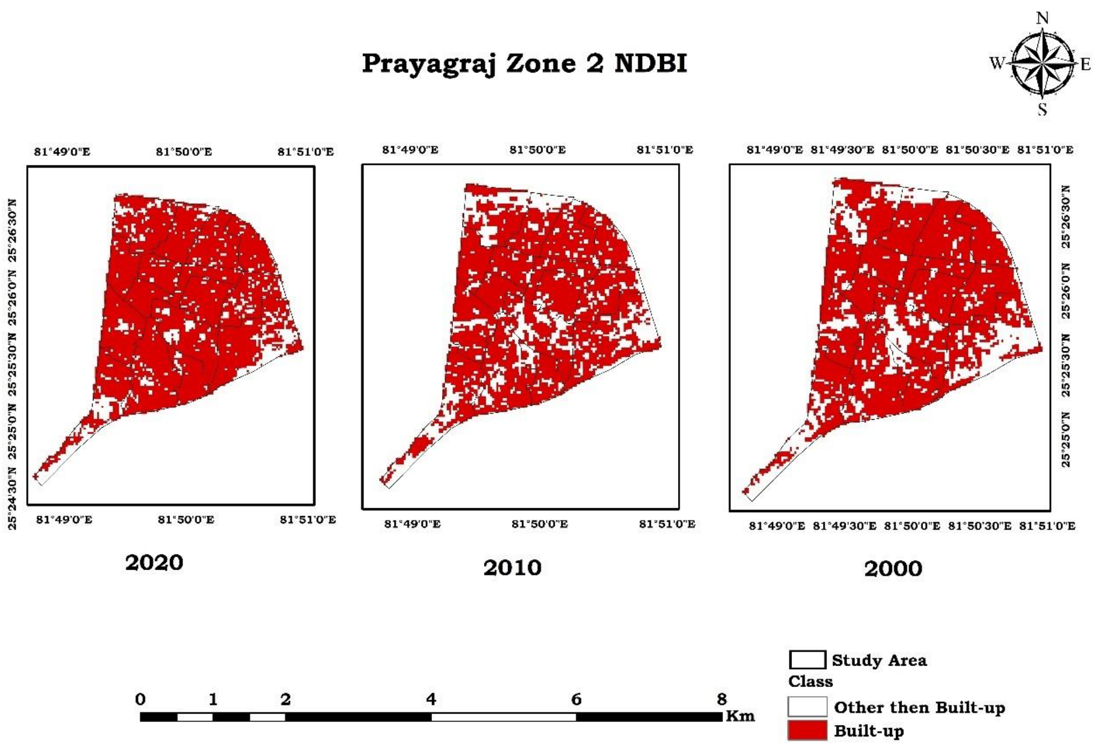
urban services. The two-decade trajectory clearly documents a near-doubling of Zone 1's built-up area.

V.I.II. ZONE 2

Zone 2, comprising wards 57, 60, 76, 77, 80, 83, 86, 87, 88, 90, 92, 95, 97, 98, 99, and 100, exhibited a somewhat different pattern of built-up change. In 2000, Zone 2 contributed 4.789 sq. km (7.18%) to the total built-up area. High NDBI concentrations were recorded in the north-western sector—particularly in Narayan Singh Nagar (ward 95) and Malviya Nagar (ward 86)—while the central ward of Atarsuiya recorded comparatively sparse built-up coverage.

Figure 2: Spatial Distribution of Normalised Difference Built-up Index (NDBI) in Zone 2 of Prayagraj City for the Years 2000, 2010 and 2020



Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

An unusual feature of Zone 2's trajectory was the marginal contraction of its built-up area between 2000 and 2010, declining from 4.789 sq. km to 4.715 sq. km. This anomalous trend likely reflects reclassification of certain mixed land covers under the NDBI threshold or localized demolition and reconstruction activity. As a share of the city's expanded built-up area, Zone 2's contribution fell sharply to 3.61% in 2010. The 2020 data, however, confirmed a resumption of growth, with Zone 2's built-up area rising to 5.424 sq. km and comprising 2.74% of the city total. Western wards 92 and 77 showed notable increments, and even the previously sparse central areas began to fill in.

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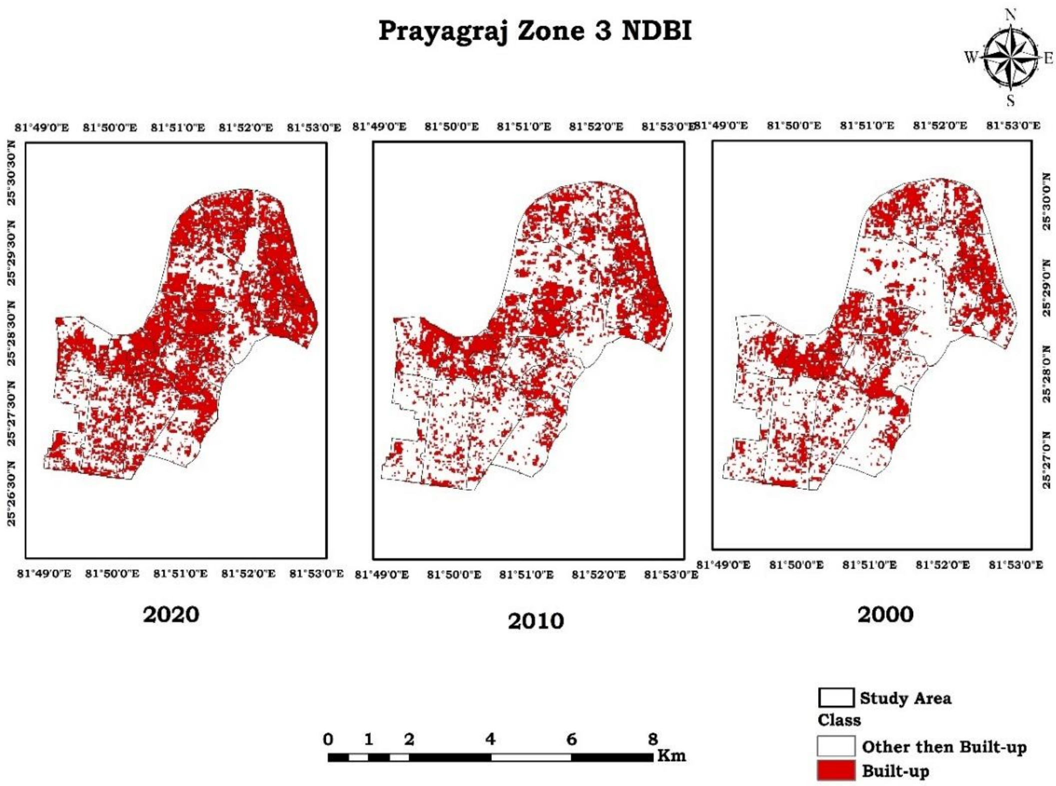
Figure 3: Spatial Distribution of Normalised Difference Built-up Index (NDBI) in Zone 3 of Prayagraj City for the Years 2000, 2010 and 2020



Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

V.I.III. ZONE 3

Zone 3 registered steady and continuous expansion of built-up area across all three decades. The zone's built-up coverage of 7.626 sq. km in 2000 accounted for 11.44% of the city total—the second highest proportional contribution among all zones at that time. High NDBI intensity was concentrated in the northern and eastern wards, including Teliyarganj (ward 55), Mehdauri (ward 64), and Govindpur (ward 72), as well as parts of the western ward of Rajapur (ward 07), while southern portions of the zone recorded considerably lower built-up concentrations.

By 2010, the area under built-up in Zone 3 had risen to 8.763 sq. km (6.70% of the city total), with the same wards continuing to exhibit the highest NDBI concentrations. The southern wards remained comparatively less developed. The most significant expansion occurred between 2010 and 2020, when Zone 3's built-up area grew by an impressive 45.7% to reach 12.772 sq. km. Civil Lines Area-1 (ward 26) and Nyay Marg (ward 68), previously characterized by relatively open landscapes, showed marked increases in NDBI values, indicating active construction and land conversion across previously undeveloped stretches.

V.I.IV. ZONE 4

Zone 4, encompassing 14 wards, contributed 7.021 sq. km (10.53%) to the city's built-up area in 2000. The eastern wards—particularly Pura Padain (ward 46), and surrounding wards 69, 48, and 36—dominated the NDBI pattern, while the southern portions of the zone recorded lower built-up density. Between 2000 and 2010, Zone 4's built-up area grew modestly to 7.822 sq.

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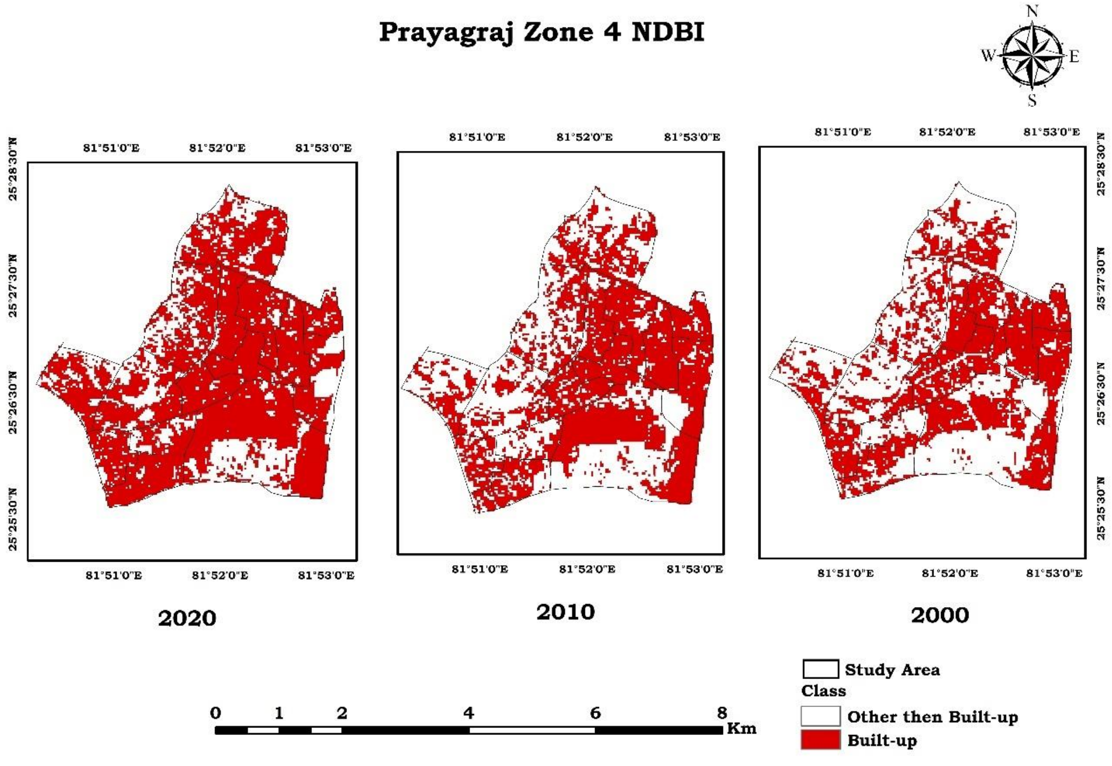
km (5.98% of the city total), with the eastern sector continuing to lead in built-up intensity. Ward 65 (Tagore Town) in the western portion retained comparatively lower NDBI values, likely on account of the higher vegetation cover in that area.

The 2020 data revealed a substantial increase across Zone 4, with built-up area reaching .962 sq. km (5.04%). The central, south-western, and south-eastern portions of the zone—previously more sparsely developed—now recorded elevated NDBI values, reflecting the penetration of urban development into formerly intermediate areas of the zone.

Figure 4: Spatial Distribution of Normalised Difference Built-up Index (NDBI) in Zone 4 of Prayagraj City for the Years 2000, 2010 and 2020



Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

V.I.V. ZONE 5

Zone 5 constitutes the largest contributor to Prayagraj's built-up area in absolute terms across all three study years. In 2000, Zone 5 accounted for 18.798 sq. km—fully 28.19% of the city's total built-up extent—though actual built-up concentrations within the zone were sparse, confined primarily to the central ward 08 (Tenduwan) and ward 70 (Mawaiya). The peripheral character of much of Zone 5's territory at that time meant that large tracts remained as agricultural or transitional land.

The decade from 2000 to 2010 witnessed the most explosive growth of Zone 5, as its built-up area more than doubled to 38.154 sq. km (29.18% of the 2010 city total). Wards 47 (Nani Dadri) and 70 (Mawaiya) in the north-eastern sector recorded the highest concentrations of new built-up development. By 2020, Zone 5 continued its rapid expansion, reaching 54.448 sq. km and maintaining its primacy among all zones with a 27.53% share of the city's total built-up area. Virtually all wards within Zone 5 participated in this growth, reflecting the broad-based character of peripheral urban expansion in this sector.

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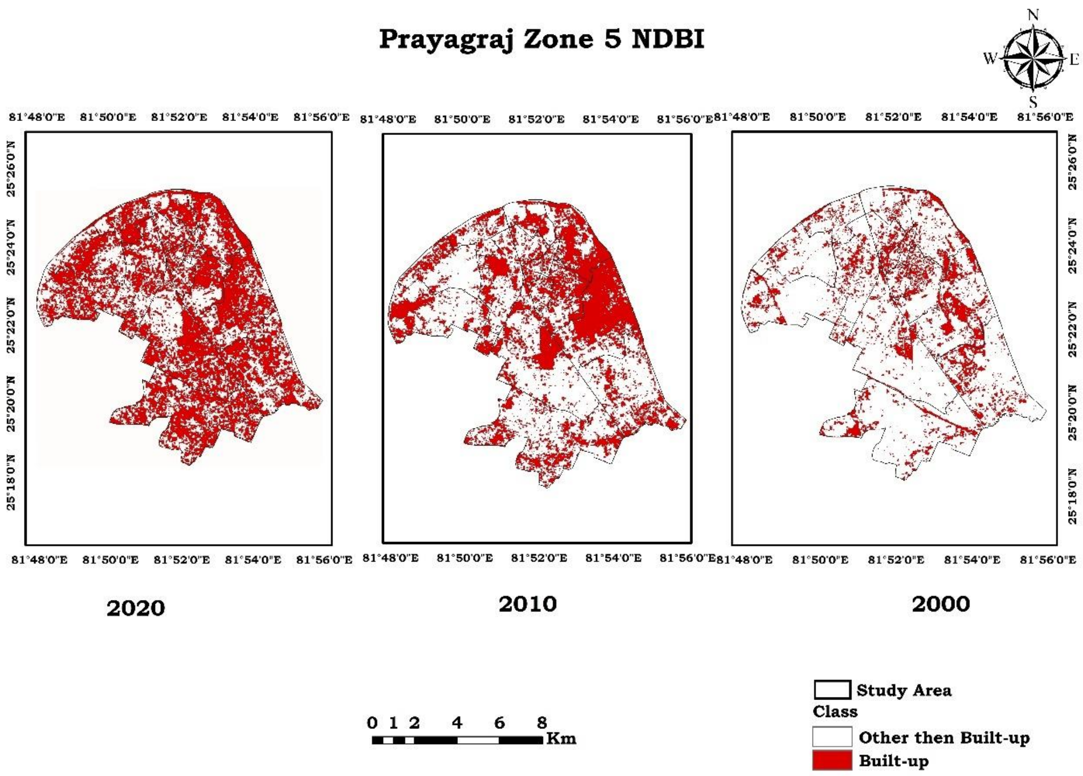
Figure 5: Spatial Distribution of Normalised Difference Built-up Index (NDBI) in Zone 5 of Prayagraj City for the Years 2000, 2010 and 2020



Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

V.I.VI. ZONE 6

Zone 6 presents one of the most dramatic narratives of built-up expansion in the study. In 2000, the zone accounted for only 10.189 sq. km (15.28%) of the city's built-up area, with modest concentrations in the northern wards (59, 79, 18, 15) and the western ward 5. However, by 2010, Zone 6's built-up area had expanded to 27.073 sq. km—a growth of nearly 166% over the decade—making it the second-largest contributor to the city's built-up area at 20.71%. This extraordinary expansion was driven by large-scale urbanization in Mundera, Transport Nagar, and Neem Sarai in the north, and by new construction in Pipalgaon and the south-eastern neighbourhood of Jhalwa.

By 2020, Zone 6's built-up coverage reached 32.979 sq. km (16.67%), with further expansion in Harwara, Jayantipur, and across the zone's interior wards. The trajectory of Zone 6 encapsulates the pattern of peri-urban transformation that has characterized Prayagraj's recent urban growth—rapid infilling of previously agricultural and vegetated fringes as the city's development frontier has pushed outward.

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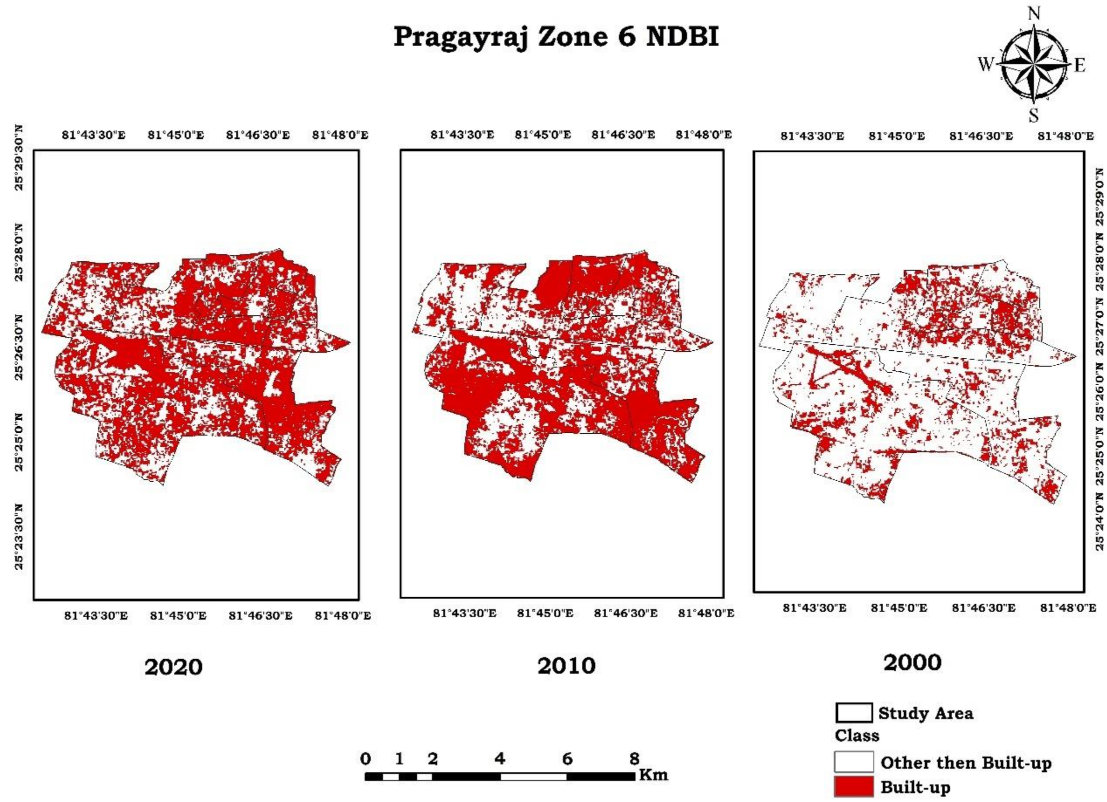
Figure 6: Spatial Distribution of Normalised Difference Built-up Index (NDBI) in Zone 6 of Prayagraj City for the Years 2000, 2010 and 2020



Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

V.I.VII. ZONE 7

Zone 7 exhibited the highest relative rate of built-up growth among all eight zones over the two-decade period. Starting from a modest base of just 4.285 sq. km in 2000—the lowest absolute built-up area of any zone—Zone 7 grew rapidly to 12.429 sq. km by 2010, an increase of nearly 190%. The eastern ward of Bahmalpur (ward 16) was among the earliest to show elevated NDBI values, while the southern wards 37 (Malak Harhar) and 56 (Phaphamau) began to demonstrate significant built-up concentration from 2010 onwards.

Figure 7: Spatial Distribution of Normalised Difference Built-up Index (NDBI) in Zone 7 of Prayagraj City for the Years 2000, 2010 and 2020

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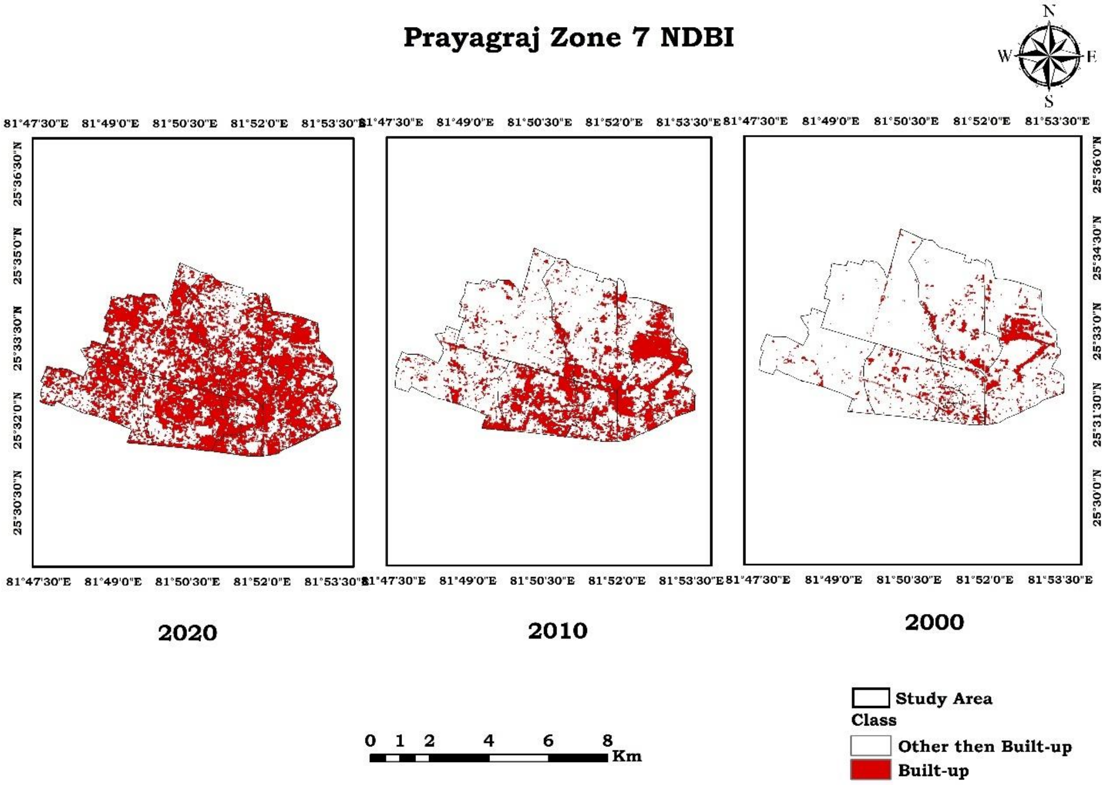
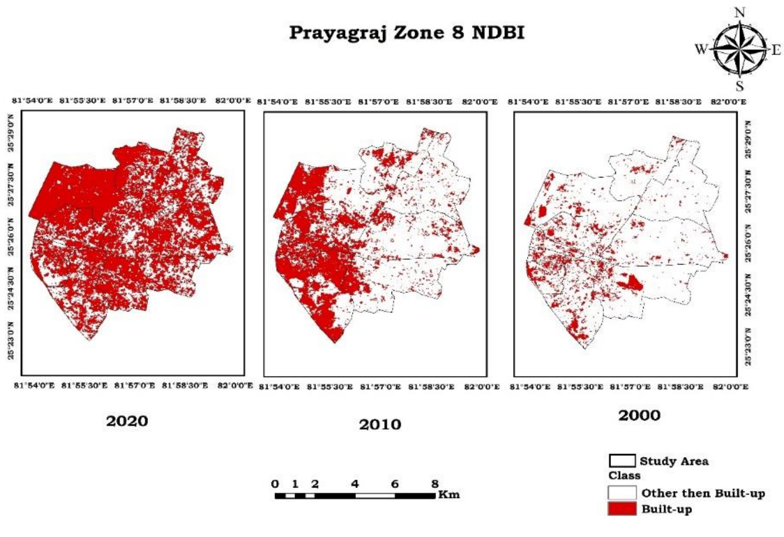


Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

By 2020, Zone 7's built-up area had reached 24.199 sq. km (12.23% of the city total), with wards 10, 14, 16, 37, 39, and 56 all exhibiting considerable intensification. The growth of Phaphamau as an emerging urban node on the northern bank of the Ganga has been particularly significant, driven by improved bridge connectivity and real estate development in the area.

Figure.8: Spatial Distribution of Normalised Difference Built-up Index (NDBI) in Zone 8 of Prayagraj City for the Years 2000, 2010 and 2020



Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

V.I.VIII. ZONE 8

Zone 8 also recorded dramatic built-up expansion, particularly between 2000 and 2010. Beginning with 8.265 sq. km in 2000 (12.39% of the city total), Zone 8 experienced a near-tripling of its built-up area to 24.216 sq. km by 2010 (18.52%). The western wards—especially wards 9, 50, 85, 75, and 52—drove this growth, with Haweliya (ward 52) and Kanihar (ward 6) showing the earliest concentrations. By 2020, Zone 8's built-up area had further expanded to 49.068 sq. km (24.81%), the second-largest absolute built-up area after Zone 5. Ward 9 (Sanauti) recorded particularly high NDBI intensities alongside widespread growth across the zone's remaining wards.

V.I.IX. COMPARATIVE ANALYSIS OF BUILT-UP AREA CHANGE (2000–2020)

Table 1 provides a comparative summary of the zone-wise built-up area data for all eight zones across the three study years.

Table 1: Zone-wise Built-up Area and Percentage Contribution in Prayagraj City (2000–2020)

Zone	**Built-up Area 2000 (sq. km)**	**% of Total (2000)**	**Built-up Area 2010 (sq. km)**	**% of Total (2010)**	**Built-up Area 2020 (sq. km)**	**% of Total (2020)**
Zone 1	5.761	8.64	7.617	5.82	9.002	4.55
Zone 2	4.789	7.18	4.715	3.61	5.424	2.74
Zone 3	7.626	11.44	8.763	6.70	12.772	6.46
Zone 4	7.021	10.53	7.822	5.98	9.962	5.04
Zone 5	18.798	28.19	38.154	29.18	54.448	27.53
Zone 6	10.189	15.28	27.073	20.71	32.979	16.67
Zone 7	4.285	6.43	12.429	9.51	24.199	12.23
Zone 8	8.265	12.39	24.216	18.52	49.068	24.81
Total	**66.69**	**100.00**	**130.75**	**100.00**	**197.81**	**100.00**

Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing analysis.

The aggregate data presented in Table 1 confirm that the total built-up area of Prayagraj city grew from 66.69 sq. km in 2000 to 130.75 sq. km in 2010 and further to 197.81 sq. km in 2020, representing an overall increase of 196.6% over the two decades. Zones 5, 6, 7, and 8—largely peripheral zones—accounted for the overwhelming majority of this growth, their combined share rising from 62.29% in 2000 to 81.29% by 2020. By contrast, the older, more centrally located zones (1–4) experienced more modest absolute growth and saw their proportional contribution to the city's built-up area decline markedly, reflecting the predominantly peripheral character of Prayagraj's recent urban expansion.

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V.II. ZONE-WISE ANALYSIS OF NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI)

The following zone-wise NDVI analysis traces the evolution of vegetation cover in Prayagraj's eight zones across 2000, 2010, and 2020. Table 2 at the end of this section summarizes the mean NDVI values, vegetation areas, and percentage contributions for all zones.

V.II.I. ZONE 1

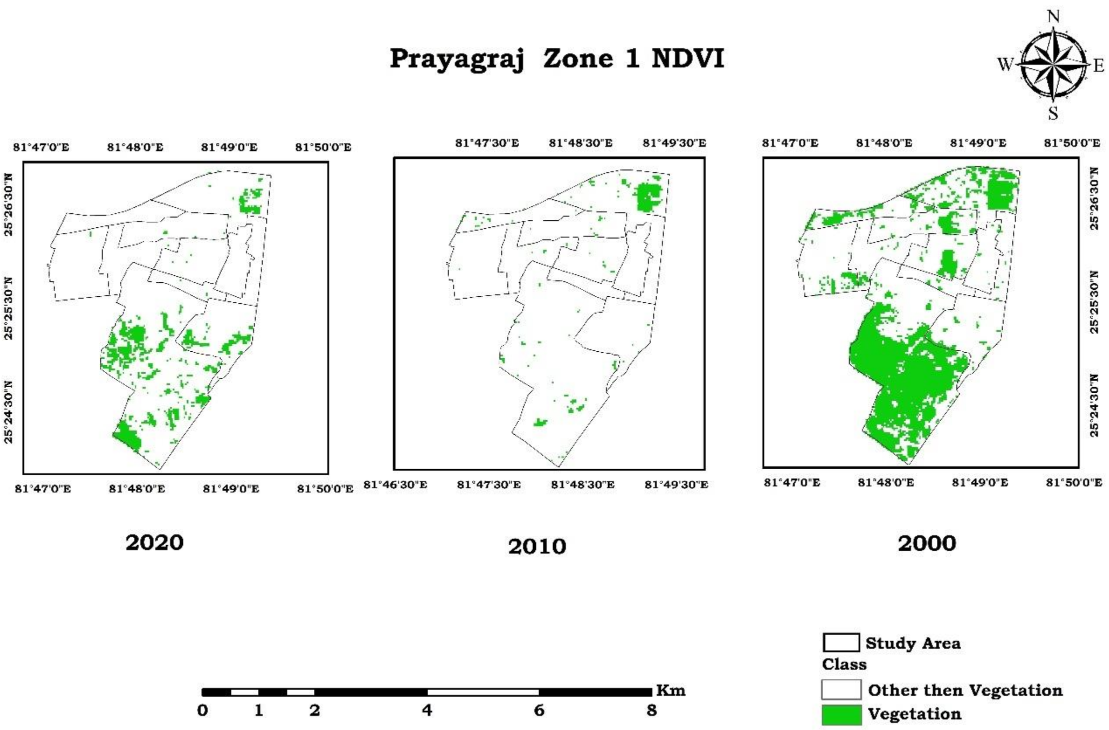
In the year 2000, Zone 1 supported a vegetation cover of 3.873 sq. km, representing 1.94% of the city's total vegetated area of 199.69 sq. km and a mean NDVI of 0.289. The southern ward of Karailabagh (ward 82) was the primary locus of vegetative concentration, together with some green cover in the north-eastern ward of Jhoolelal Nagar (ward 28). By 2010, however, Zone 1's vegetation had contracted sharply to only 0.333 sq. km (0.75% of the city total) and a mean NDVI of 0.195—the lowest recorded for this zone over the study period—as rapid urbanization removed tree cover and open green spaces. Only ward 28 retained a discernible concentration of vegetation.

The 2020 data, however, indicated a recovery: Zone 1's vegetation area rebounded to 1.042 sq. km (1.84% of city total) with a mean NDVI of 0.223, with renewed vegetative presence in both wards 82 and 28. This partial recovery likely reflects afforestation initiatives, roadside tree planting, and the maturation of vegetation in newer developments.

V.II.II. ZONE 2

Zone 2 consistently exhibited the most limited vegetation cover among all eight zones throughout the study period, reflecting the highly dense and built-up character of this inner-city zone. From an already modest 0.540 sq. km in 2000 (mean NDVI: 0.207), vegetation

Figure.9: Spatial Distribution of Normalized Difference Vegetation Index (NDVI) in Zone 1 of Prayagraj City for the Years 2000, 2010 and 2020



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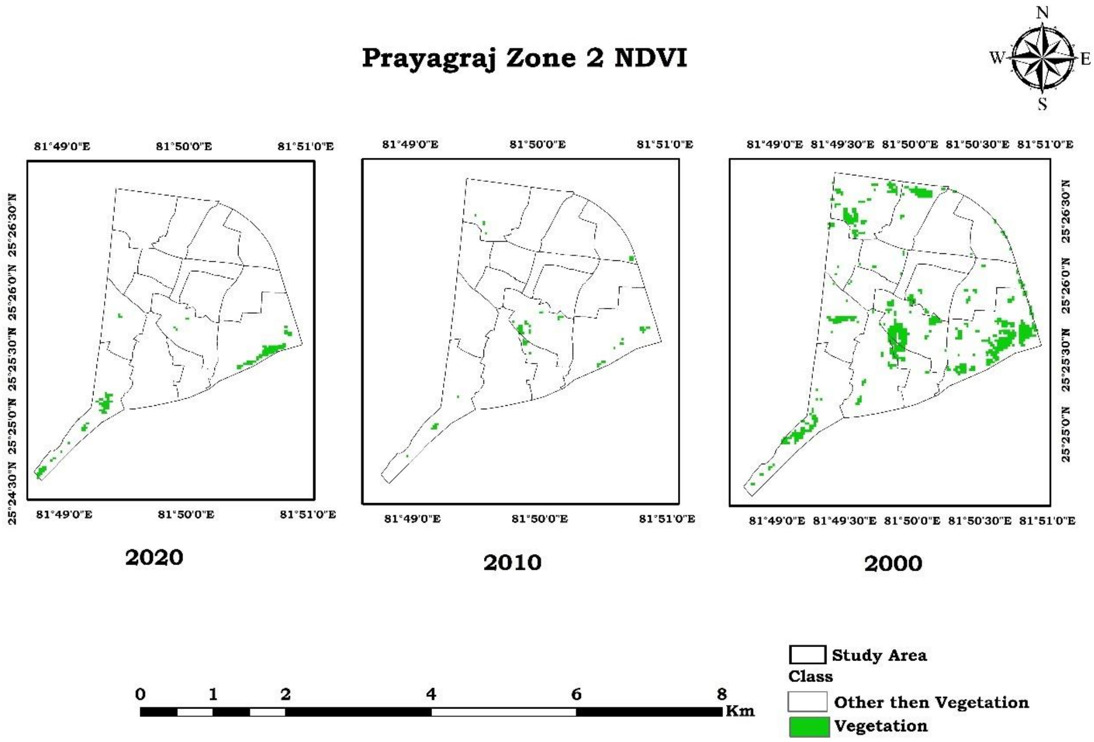
Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

coverage plummeted to just 0.051 sq. km in 2010 (mean NDVI: 0.132), with only fragments in ward 76 (Atarsuiya) and isolated patches elsewhere. A marginal recovery to 0.113 sq. km was recorded by 2020 (mean NDVI: 0.141), primarily in Kashiraj Nagar (ward 57). These consistently low NDVI values underscore the severely constrained green infrastructure of Zone 2 and its implications for local thermal conditions.

V.II.III. ZONE 3

Zone 3 was one of the better-vegetated zones in 2000, supporting 10.513 sq. km of vegetated cover (5.26% of city total) with a mean NDVI of 0.345. The Cantonment area, Civil Lines, and wards 61 (Colonelganj) and 26 provided significant tree cover. By 2010, vegetation area had declined to 4.256 sq. km (9.57% of a now much smaller total city vegetation area), with

Figure 10: Spatial Distribution of Normalized Difference Vegetation Index (NDVI) in Zone 2 of Prayagraj City for the Years 2000, 2010 and 2020



Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

NDVI dropped to 0.250 as urban densification encroached on previously green spaces. A further decline to 2.418 sq. km (mean NDVI: 0.238) was recorded in 2020, though the Cantonment area and southern wards continued to sustain some vegetative cover. Unlike most other zones, Zone 3 showed no vegetation recovery between 2010 and 2020, pointing to continued development pressure in this sector.

V.II.IV. ZONE 4

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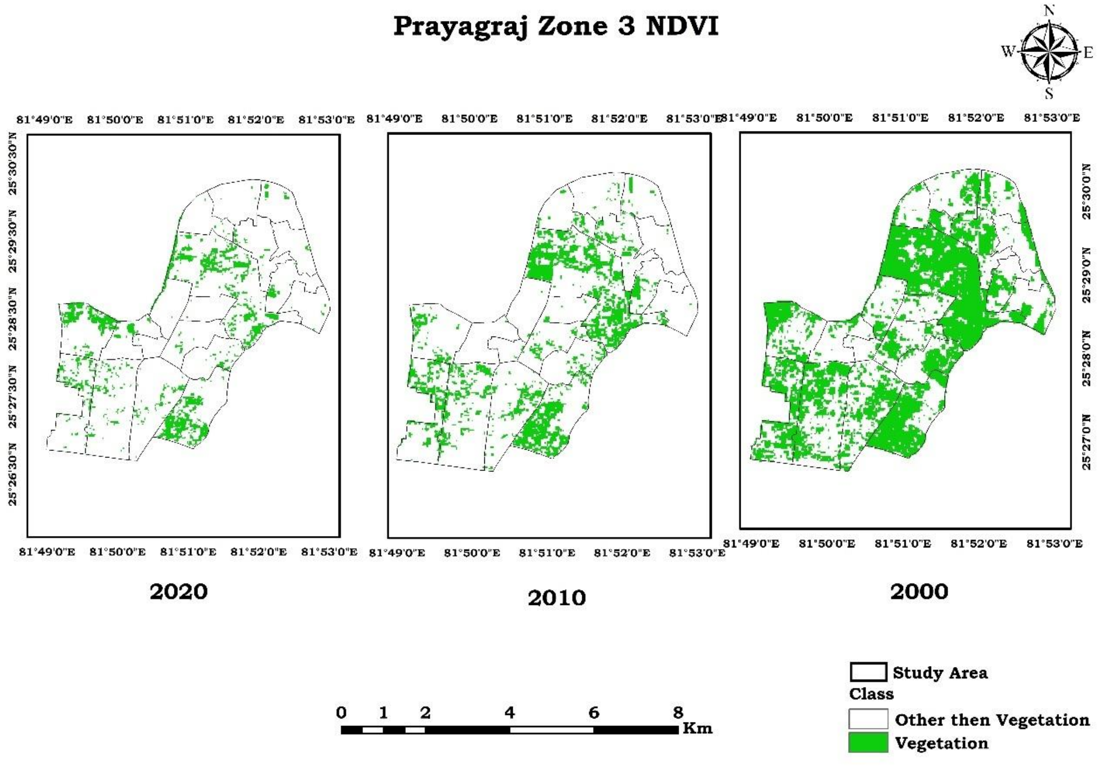
Zone 4 registered a progressive decline in vegetation across all three study years. From 3.373 sq. km in 2000 (mean NDVI: 0.273), vegetation shrank to 1.288 sq. km in 2010 (mean NDVI: 0.205) and further to 0.505 sq. km in 2020 (mean NDVI: 0.182). The northern ward (Alenganj, ward 32) and the southern Cantonment area retained the most consistent vegetative presence over the period, while the central and eastern wards experienced near-complete removal of vegetation cover as construction activity intensified. By 2020, Zone 4's proportional share of city vegetation had fallen to just 0.89%—a dramatic reduction from its already modest 1.69% in 2000.

Figure 11: Spatial Distribution of Normalized Difference Vegetation Index (NDVI) in Zone 3 of Prayagraj City for the Years 2000, 2010 and 2020



Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

V.II.V. ZONE 5

Zone 5 dominated Prayagraj's total vegetation cover in absolute terms throughout the study period. In 2000, Zone 5 supported 64.693 sq. km of vegetated area (32.40% of city total) with the highest mean NDVI of any zone at 0.435, reflecting the abundant agricultural fields, open spaces, and semi-natural vegetation that characterized this predominantly peripheral zone at the time. South-western wards (Tenduwan, ward 08; Nibi Tuluka Khurd, ward 04) and the north-eastern periphery were especially green.

Figure 12: Spatial Distribution of Normalized Difference Vegetation Index (NDVI) in Zone 4 of Prayagraj City for the Years 2000, 2010 and 2020

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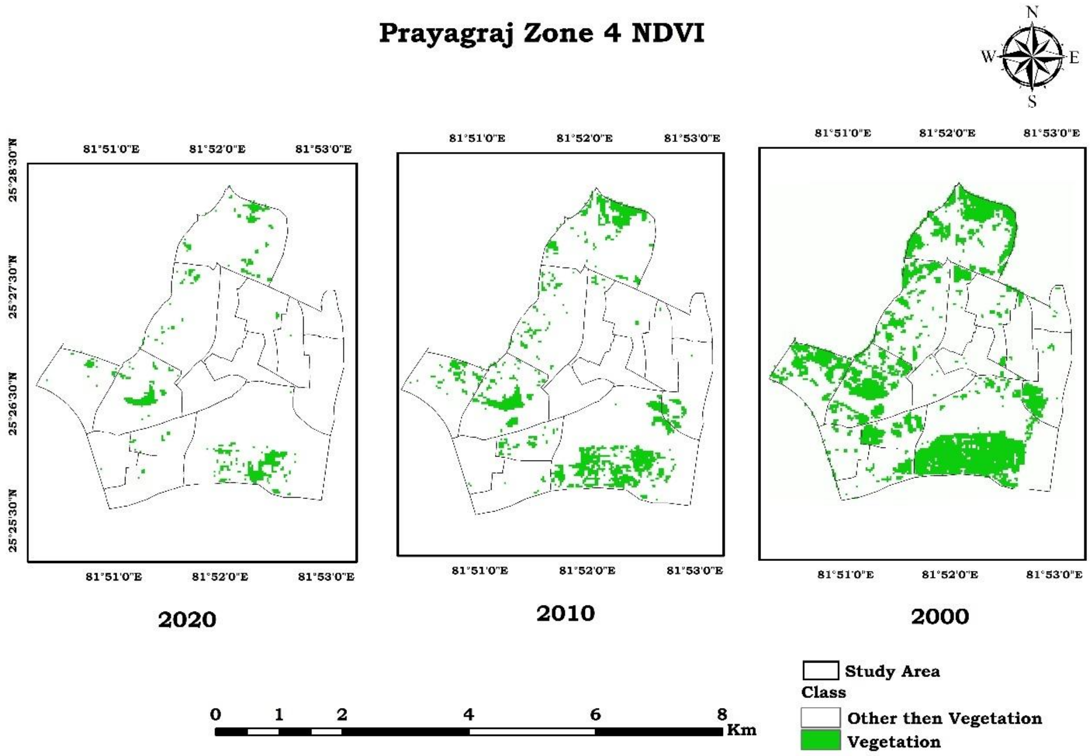

Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

The decade from 2000 to 2010 brought severe vegetation loss in Zone 5, with coverage falling by nearly two-thirds to 22.492 sq. km (mean NDVI: 0.292) as the zone became the primary frontier of Prayagraj's urban expansion. A partial recovery was observed by 2020, with vegetation area increasing to 26.011 sq. km (mean NDVI: 0.296, 45.86% of city total), possibly reflecting the greening of newly laid-out residential colonies and park provision within planned developments. Nonetheless, the 2020 vegetation extent remained far below the 2000 baseline.

Figure 13: Spatial Distribution of Normalized Difference Vegetation Index (NDVI) in Zone 5 of Prayagraj City for the Years 2000, 2010 and 2020

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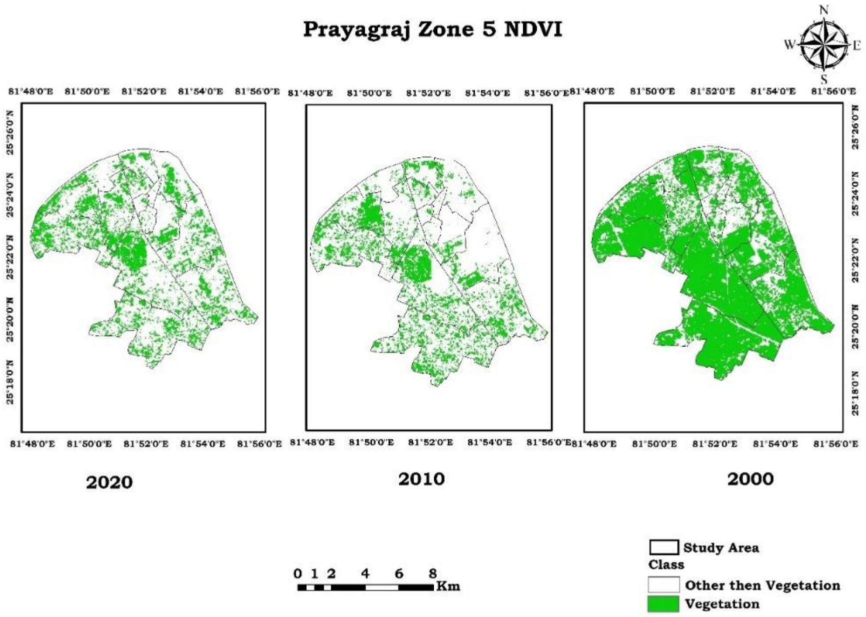
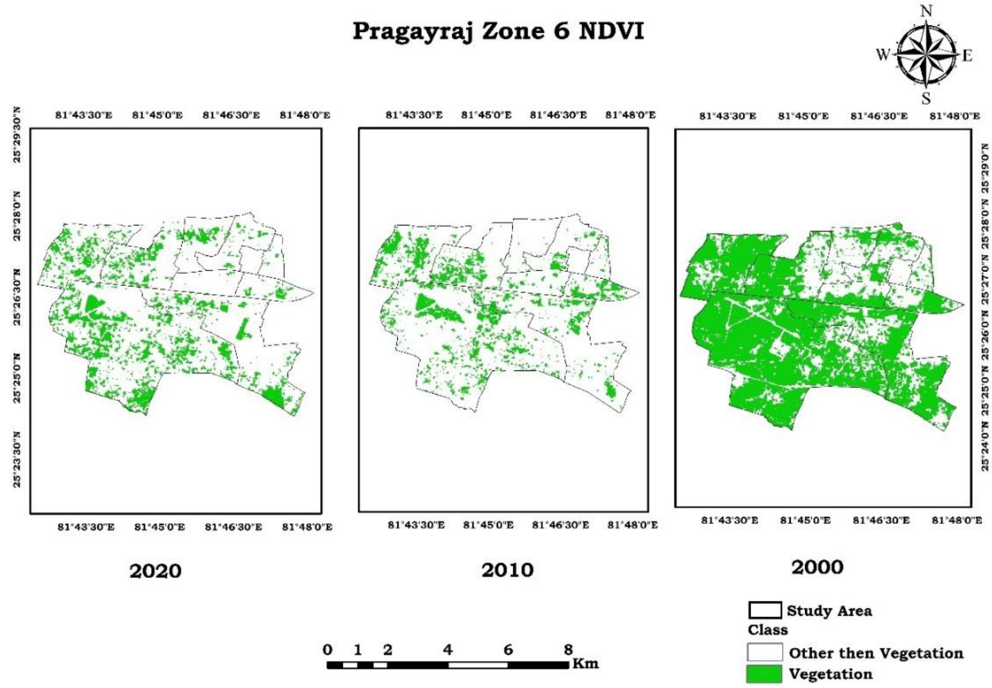


Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

V.II.VI. ZONE 6

Zone 6 was extensively forested and vegetated in 2000, with 27.503 sq. km of vegetation cover (13.77% of city total) and a mean NDVI of 0.404. Wards such as Bhambrauli Uparhar (ward 3), Pipalgaon (ward 5), and Jhalwa (ward 35) were fully canopied with trees and forest patches. However, the dramatic urban expansion in this zone—documented earlier in the NDBI analysis—caused a precipitous decline in vegetation to 6.675 sq. km by 2010 (mean NDVI: 0.269). A modest recovery to 8.273 sq. km (mean NDVI: 0.275) was observed by 2020, concentrated in the south and west of the zone. The transformation of Zone 6 from an extensively green fringe to a largely built-up urban area within a single decade represents one of the most profound examples of urban land conversion in Prayagraj's recent history.

Figure 14: Spatial Distribution of Normalized Difference Vegetation Index (NDVI) in Zone 6 of Prayagraj City for the Years 2000, 2010 and 2020



Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

V.II.VII. ZONE 7

Zone 7 recorded 33.284 sq. km of vegetation in 2000 (16.67% of city total, mean NDVI: 0.425), reflecting the extensive agricultural and semi-natural landscapes of this then-peripheral zone. Wards 10 (Gohari), 14 (Bhadri), 39 (Malak Harhar), and 16 (Bahmalpur) were particularly well-vegetated. By 2010, vegetation had declined sharply to 3.872 sq. km (mean NDVI: 0.265), with only ward 39 maintaining appreciable green cover. Between 2010 and 2020, however, Zone 7 exhibited the largest absolute vegetation recovery of any zone: vegetation area doubled to 7.769 sq. km (mean NDVI: 0.276), with renewed growth in the northern wards (10 and 16) and visible recovery in the western and eastern sectors of the zone.

Figure.15: Spatial Distribution of Normalized Difference Vegetation Index (NDVI) in Zone 7 of Prayagraj City for the Years 2000, 2010 and 2020

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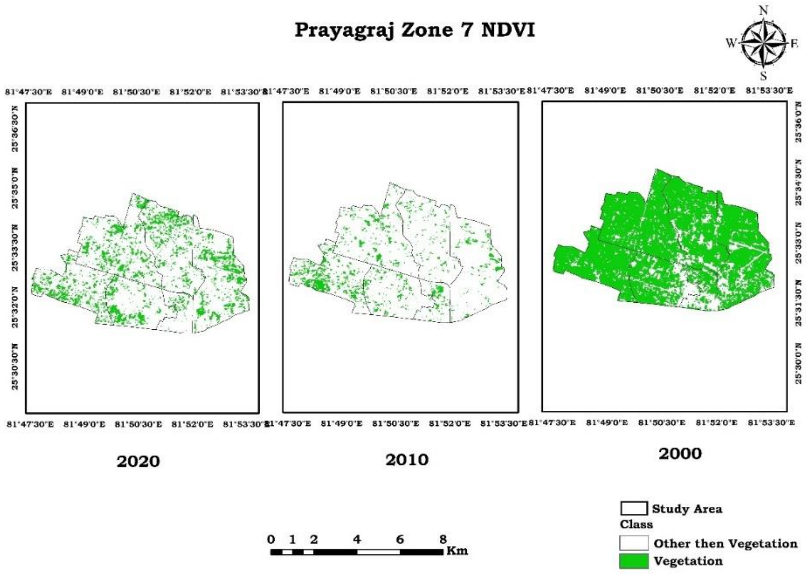


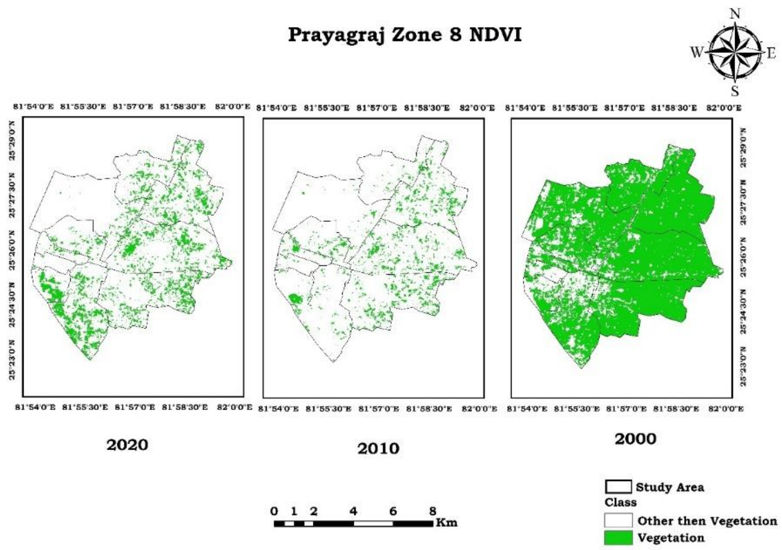
Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

V.II.VIII. ZONE 8

Zone 8 possessed the highest absolute vegetation area among all zones in 2000, with 55.949 sq. km (28.02% of city total, mean NDVI: 0.430). Wards 11 (Amarsapur), 19 (Andawa), 6 (Kanihar), and 9 (Sanauti) were characterized by substantial forest and agricultural cover. The decade to 2010 saw a devastating 90% reduction in Zone 8's vegetation to just 5.556 sq. km—the most severe absolute loss of any zone—as rapid urbanization consumed its green landscapes.

Only scattered traces of vegetation persisted in some wards. By 2020, vegetation area had recovered somewhat to 10.626 sq. km (mean NDVI: 0.251, 18.73% of city total), with eastern wards 19 and 6 showing renewed vegetative presence alongside southern and western areas of the zone.

Figure 16: Spatial Distribution of Normalized Difference Vegetation Index (NDVI) in Zone 8 of Prayagraj City for the Years 2000, 2010 and 2020



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Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

V.II.IX. COMPARATIVE ANALYSIS OF VEGETATION CHANGE (2000–2020)

The comparative NDVI data presented in Table 2 reveal a city-wide pattern of catastrophic vegetation loss between 2000 and 2010, followed by partial recovery from 2010 to 2020. The total area under vegetation in Prayagraj declined from 199.69 sq. km in 2000 to 44.49 sq. km in 2010—a reduction of approximately 77.72%—before recovering modestly to 56.72 sq. km in 2020. Mean NDVI values declined across all eight zones between 2000 and 2010, reflecting not merely areal reduction but also deterioration in the health and density of remaining vegetation. The peripheral zones (5, 6, 7, and 8) bore the brunt of absolute vegetation loss in the first decade, while the partial recovery observed in the second decade was distributed somewhat more evenly across the city.

Table 2: Zone-wise Mean NDVI, Vegetation Area and Percentage Contribution in Prayagraj City (2000–2020)

Zone	Mean NDVI			Vegetation Area (sq. km)			% of Total Vegetation		
	2000	2010	2020	2000	2010	2020	2000	2010	2020
Zone 1	0.289	0.195	0.223	3.873	0.333	1.042	1.94	0.75	1.84
Zone 2	0.207	0.132	0.141	0.540	0.051	0.113	0.27	0.11	0.20
Zone 3	0.345	0.250	0.238	10.513	4.256	2.418	5.26	9.57	4.26
Zone 4	0.273	0.205	0.182	3.373	1.288	0.505	1.69	2.90	0.89
Zone 5	0.435	0.292	0.296	64.693	22.492	26.011	32.40	50.55	45.86
Zone 6	0.404	0.269	0.275	27.503	6.675	8.273	13.77	15.00	14.59
Zone 7	0.425	0.265	0.276	33.284	3.872	7.769	16.67	8.70	13.70
Zone 8	0.430	0.253	0.251	55.949	5.556	10.626	28.02	12.49	18.73
Total	—	—	—	**199.69**	**44.49**	**56.72**	**100.00**	**100.00**	**100.00**

Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

V.III. ZONE-WISE ANALYSIS OF LAND SURFACE TEMPERATURE (LST)

The following section documents the zone-wise temporal evolution of LST in Prayagraj between 2000 and 2020. Key LST statistics for all zones and years are summarized in Table 3.

V.III.I. ZONE 1

Zone 1 experienced a dramatic escalation in land surface temperatures over the study period. In 2000, surface temperatures ranged from a minimum of 17.60°C to a maximum of 28.33°C, with a mean LST of 22.61°C and a standard deviation of 1.58°C. The highest temperatures were concentrated in the western wards (71 and 82—Om Prakash Nagar and Karailabagh), attributable

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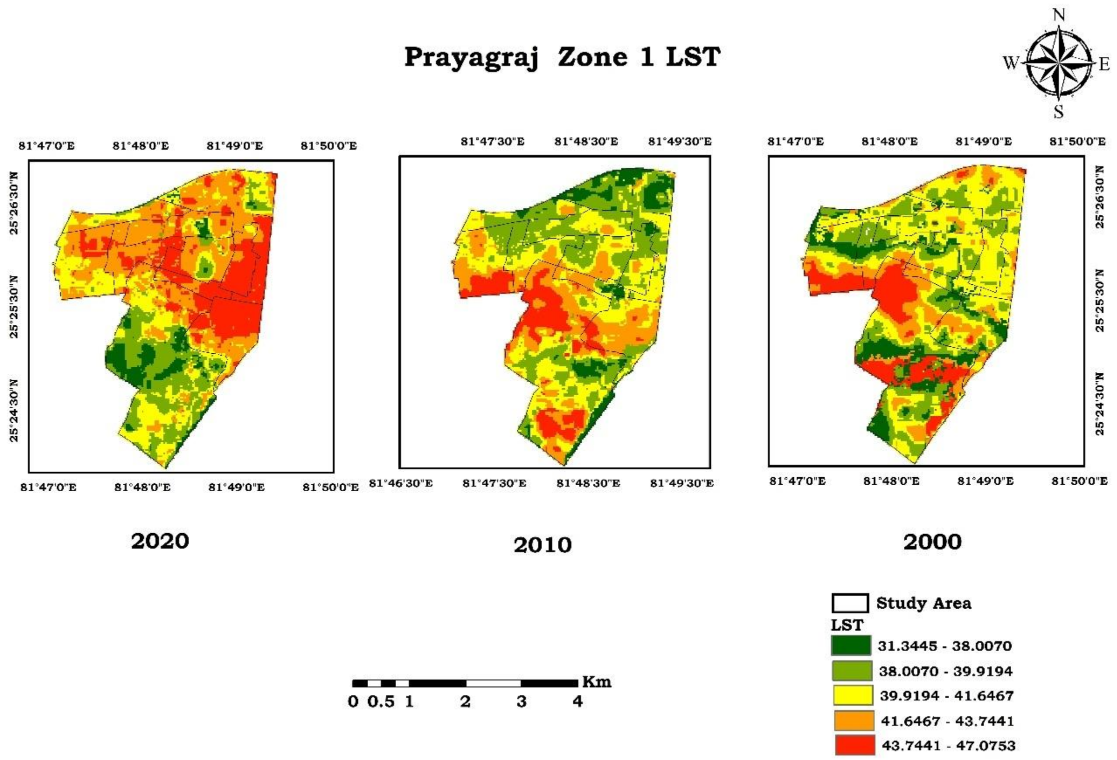
to the higher built-up density in those areas. The more vegetated southern and north-western wards recorded comparatively lower temperatures.

By 2010, the mean LST had risen to 40.91°C—an increase of more than 18°C over the decade—while the temperature range expanded dramatically to 31.34°C–47.08°C, with a standard deviation of 2.28°C reflecting increased spatial variability. The northern-eastern ward continued to show some thermal mitigation owing to residual vegetation. By 2020, the mean LST moderated to 37.30°C (range: 30.40°C–40.73°C; SD: 1.56°C), with the eastern wards (91, 93, 96) now recording higher temperatures as built-up density there intensified. The slight decline in mean LST from 2010 to 2020 is consistent with the partial recovery of vegetation cover observed in the NDVI analysis.

Figure 17: Spatial Distribution of Land Surface Temperature (LST) in Zone 1 of Prayagraj City for the Years 2000, 2010 and 2020



Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

V.III.II. ZONE 2

Zone 2's LST profile reflects its dense, built-up inner-city character. In 2000, temperatures ranged from 19.25°C to 26.82°C (mean: 22.87°C; SD: 0.88°C), with the southern and northern peripheries of the zone recording the highest values. The mean LST rose sharply to 39.47°C by 2010 (range: 30.51°C–46.38°C; SD: 2.16°C), with wards 77 and 76 registering elevated temperatures. The 2020 data indicated a slight decline in mean LST to 37.99°C (range: 28.56°C–41.19°C; SD: 1.55°C), with the Bakshi Bazar and Chauk Ganga Das areas remaining thermally stressed. Zone 2 consistently recorded higher mean temperatures than might be expected given its modest built-up growth, reflecting the thermal mass of its existing dense urban fabric.

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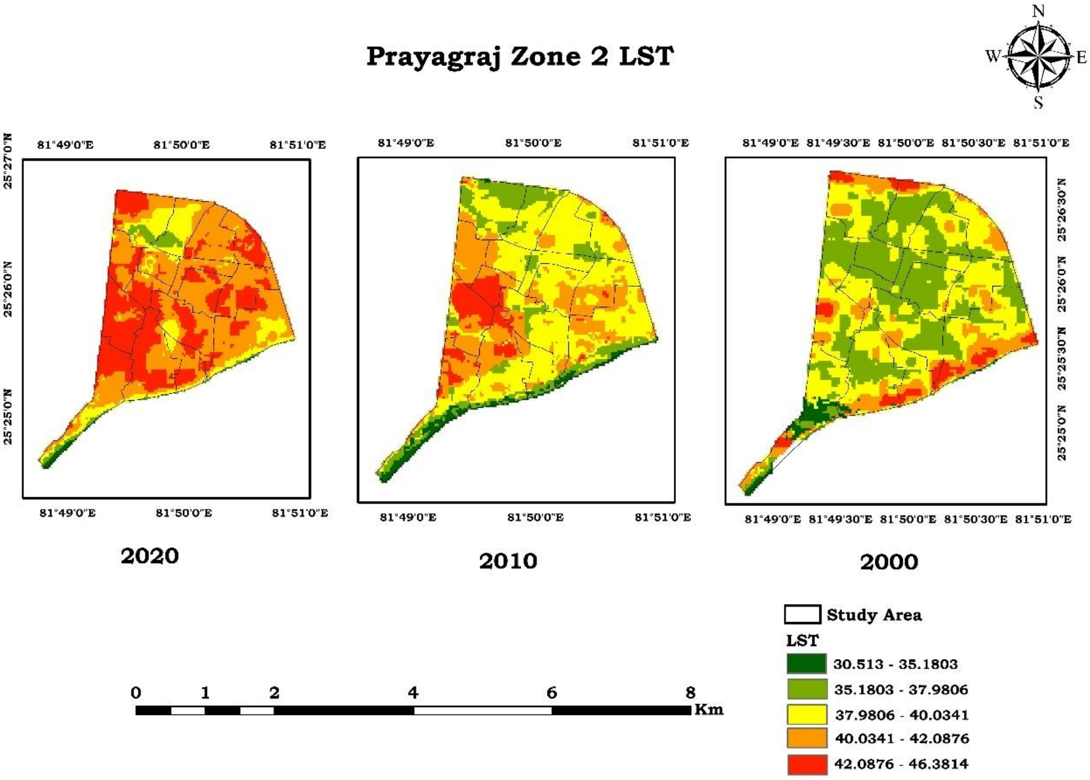
Figure 18: Spatial Distribution of Land Surface Temperature (LST) in Zone 2 of Prayagraj City for the Years 2000, 2010 and 2020

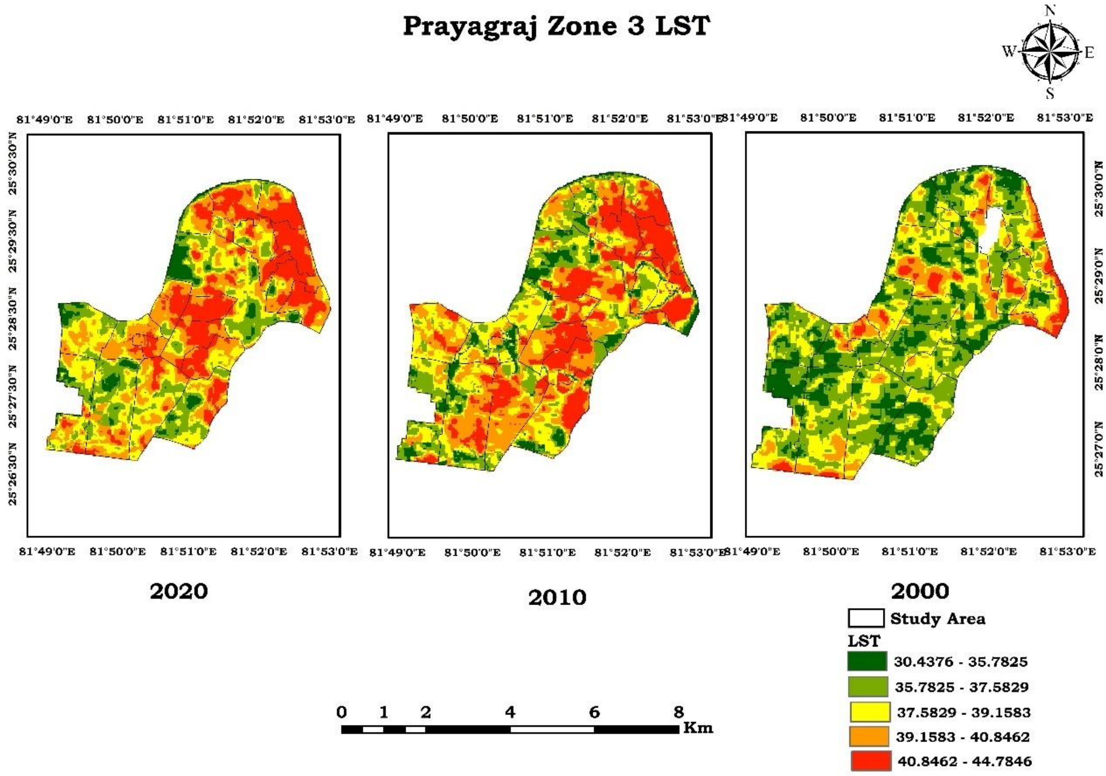


Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

V.III.III. ZONE 3

The minimum land surface temperatures of zone 3 were recorded 19.42°C in the year 2000 and the maximum LST were 27.75°C. In the year 2000, LST was mainly recorded in the periphery of zone 3 whereas in the central regions surface temperatures were comparatively lesser. The mean land surface temperatures were 37.99°C. The minimum LST increased about 11°C in 2010 and reached about 30.43°C. The maximum temperatures were recorded 44.78°C. The north eastern region especially the ward number 34,72,23 (Shivkuti, Govindpur and Sadiyabad) recorded high temperatures whereas the central region also had high temperatures. The southeast parts of Zone 3 were cooler. The mean land surface temperatures of 2010 were 39.11°C. In the year 2020 the LST varied from 30.89 °C to 41.38°C. The high temperatures continued to concentrate in north eastern regions of zone 3 whereas south west region still recorded cooler temperatures. The LST recorded for the year 2020 was comparatively lesser than the year 2010.

Figure 19: Spatial Distribution of Land Surface Temperature (LST) in Zone 3 of Prayagraj City for the Years 2000, 2010 and 2020



Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

V.III.IV. ZONE 4

Zone 4 registered mean LST values of 23.30°C in 2000 (range: 19.42°C–27.82°C; SD: 1.27°C), rising to 40.80°C in 2010 (range: 31.84°C–48.66°C; SD: 2.50°C)—the highest standard deviation in 2010 among all zones, indicating considerable within-zone thermal heterogeneity. The southern Cantonment wards recorded higher temperatures owing to their built-up character, while the northern wards (particularly ward 32, Alenganj) showed some thermal relief associated with tree cover. In 2020, mean LST declined to 38.35°C (range: 30.73°C–43.05°C; SD: 1.59°C), with the western areas recording moderate temperatures and the Cantonment contributing cooler readings owing to its maintained vegetation.

Figure 20: Spatial Distribution of Land Surface Temperature (LST) in Zone 4 of Prayagraj City for the Years 2000, 2010 and 2020

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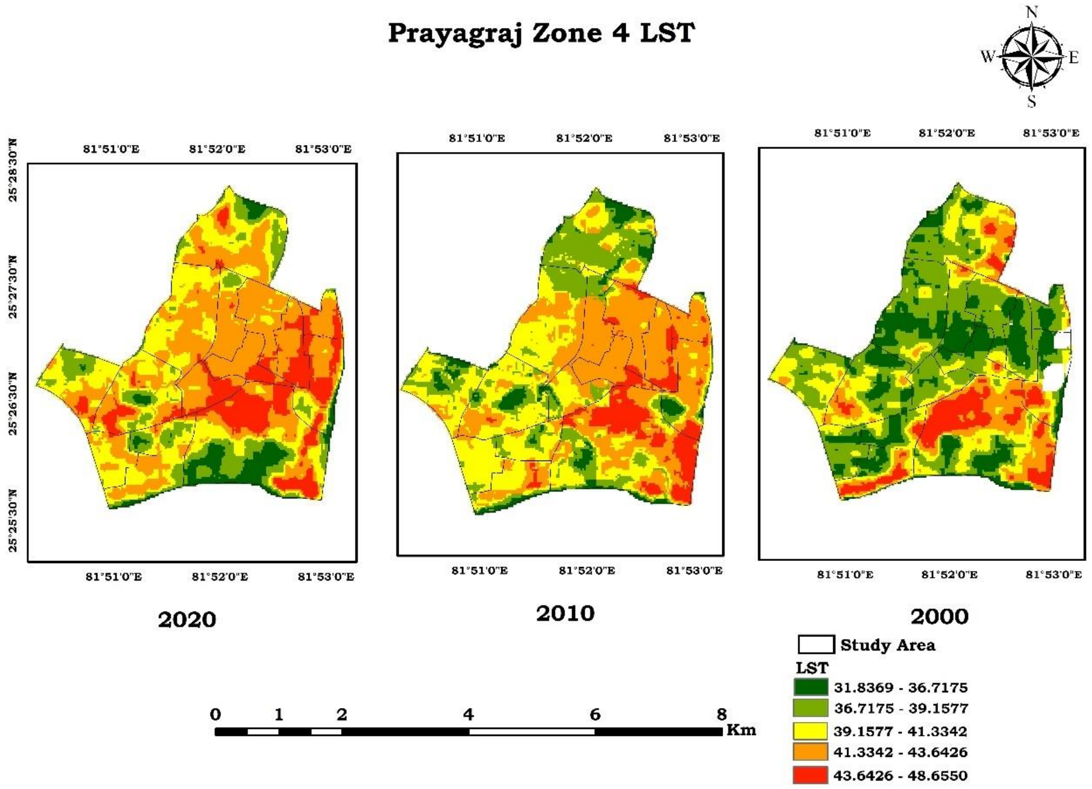

Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

V.III.V. ZONE 5

Zone 5's thermal profile is particularly noteworthy given its large spatial extent and transformation from a predominantly rural-agricultural landscape in 2000 to a partially urbanized zone by 2020. In 2000, mean LST was 23.44°C (range: 16.82°C–29.65°C; SD: 1.52°C)—the widest range among all zones in that year, reflecting the diversity of land covers within this large zone. By 2010, mean LST had jumped to 40.22°C (range: 30.71°C–50.01°C; SD: 2.80°C), with the maximum of 50.01°C the highest recorded across all zones and years in the study. Wards 33 and 4 registered particularly extreme surface temperatures. By 2020, mean LST moderated to 35.79°C (range: 27.23°C–44.62°C; SD: 1.86°C)—among the lowest mean values of all zones in that year—partly on account of the vegetation recovery documented in Zone 5's NDVI analysis.

Figure 21: Spatial Distribution of Land Surface Temperature (LST) in Zone 5 of Prayagraj City for the Years 2000, 2010 and 2020

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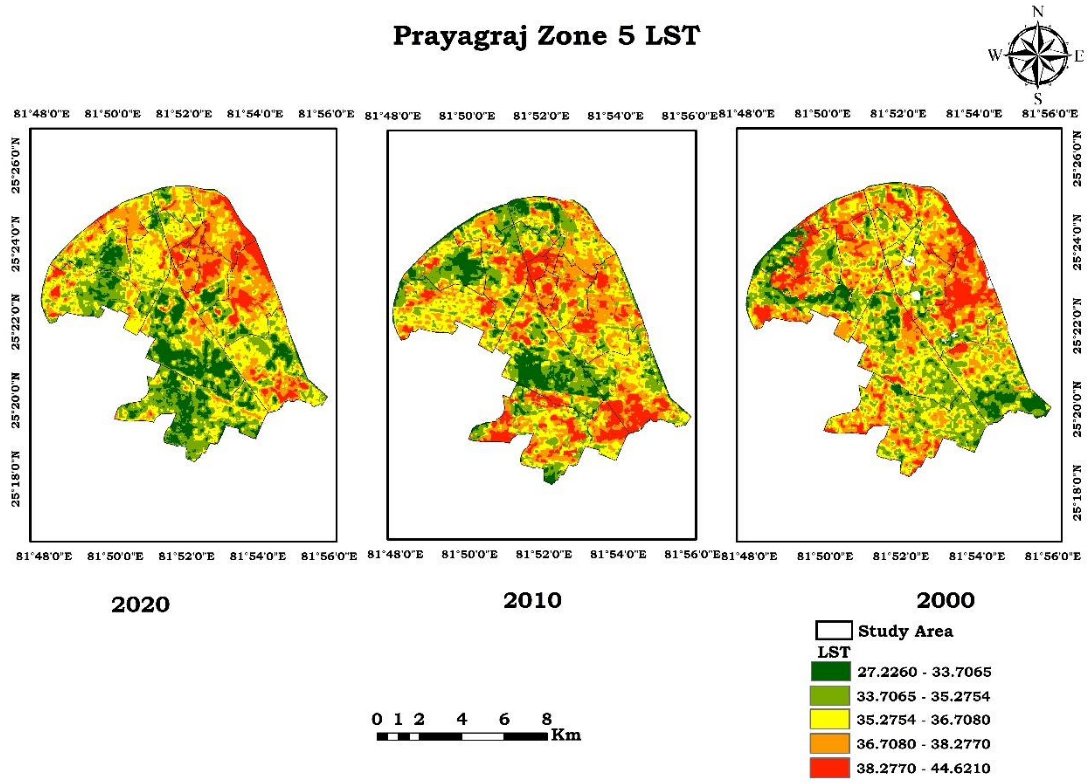

Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

V.III.VI. ZONE 6

Zone 6 exhibited a pattern of extreme LST amplification between 2000 and 2010. Starting from a mean LST of 23.22°C in 2000 (range: 17.70°C–28.50°C; SD: 1.64°C), the zone's mean temperature rose to 41.44°C by 2010 (range: 32.51°C–50.07°C; SD: 2.70°C)—the highest mean LST of any zone in 2010. This reflects the unprecedented scale of vegetation removal and built-up construction in Zone 6 during that decade. The northern and south-eastern sectors recorded the most extreme temperatures, while the western and eastern peripheries retained some thermal relief. By 2020, mean LST declined to 35.96°C (range: 29.84°C–43.77°C; SD: 1.41°C), with the north-western sector benefiting from partial regreening and the outskirts of the zone maintaining cooler conditions.

Figure 22: Spatial Distribution of Land Surface Temperature (LST) in Zone 6 of Prayagraj City for the Years 2000, 2010 and 2020

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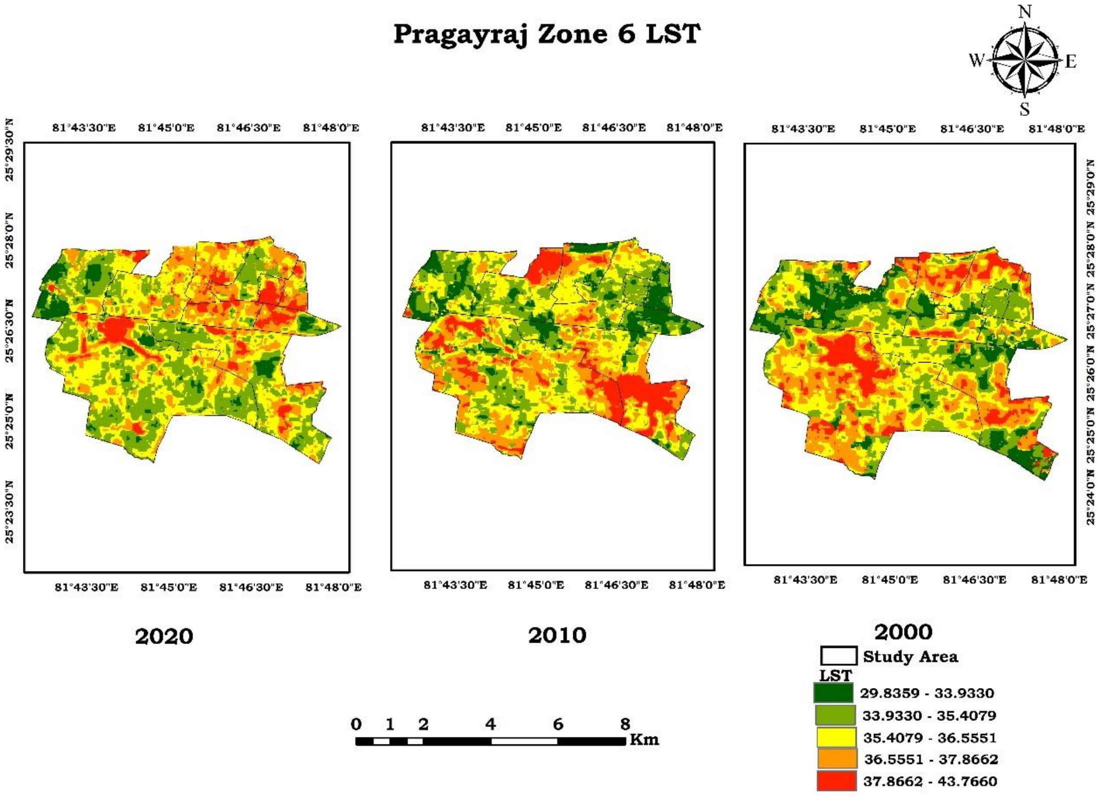

Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

V.III.VII. ZONE 7

Zone 7 recorded the lowest mean LST in 2010 among all eight zones at 36.93°C, despite experiencing significant built-up growth during that period. This lower thermal intensity may reflect the zone's relatively lower initial built-up density and the retention of some vegetative cover in its peripheral wards. In 2000, the mean LST was 23.06°C (range: 19.39°C–27.83°C; SD: 1.36°C), with the northern and south-western areas cooled by vegetation. The south-eastern sector recorded higher temperatures. By 2010, mean LST rose to 36.93°C (range: 29.80°C–45.96°C; SD: 2.89°C)—the highest SD of any zone in 2010—indicating strong spatial heterogeneity. The 2020 mean LST of 35.80°C (range: 29.73°C–41.03°C; SD: 1.56°C) showed a marginal decline, consistent with partial vegetation recovery in the northern wards.

Figure 23: Spatial Distribution of Land Surface Temperature (LST) in Zone 7 of Prayagraj City for the Years 2000, 2010 and 2020

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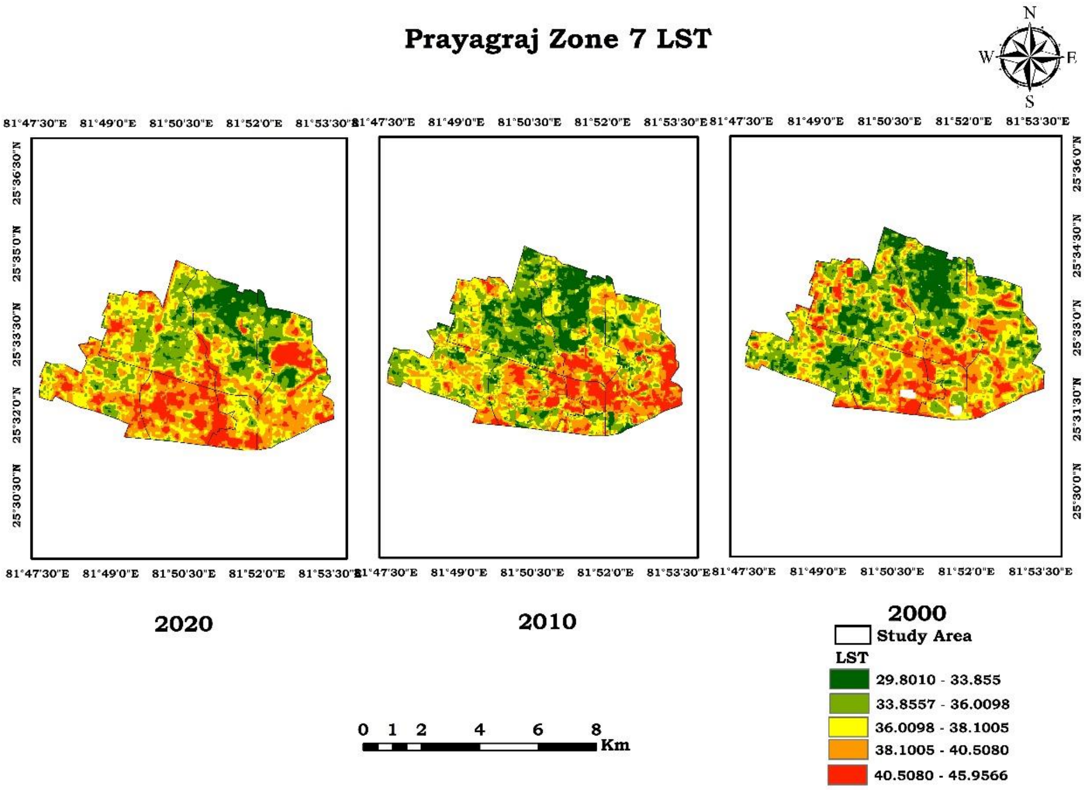

Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

V.III.VIII. ZONE 8

Zone 8's LST trajectory mirrors its pattern of dramatic built-up expansion and concomitant vegetation loss. From a mean LST of 23.60°C in 2000 (range: 18.83°C–28.62°C; SD: 1.36°C)—the highest 2000 mean LST of any zone—the zone's temperature rose to 40.34°C by 2010 (range: 29.83°C–49.37°C; SD: 2.56°C). The western wards were the hottest, consistent with the rapid built-up growth in that sector. A 2020 mean of 36.11°C (range: 29.40°C–43.61°C; SD: 1.84°C) indicated moderate thermal decline, with the north-eastern wards benefiting from vegetation recovery while the western sector remained thermally elevated.

Figure 24: Spatial Distribution of Land Surface Temperature (LST) in Zone 5 of Prayagraj City for the Years 2000, 2010 and 2020

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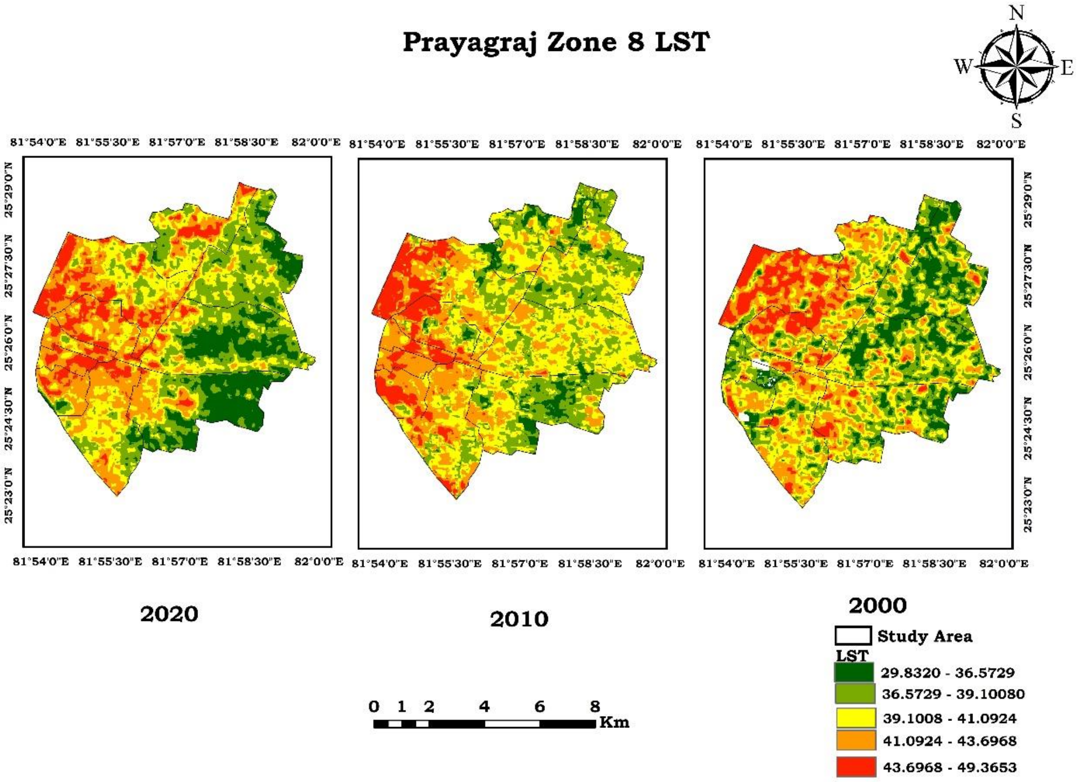

Source: Computed and prepared by the researcher using Landsat satellite imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

V.III.IX. COMPARATIVE ANALYSIS OF LST VARIATION (2000–2020)

Table.3 summarizes the LST statistics for all eight zones across the three study years. The data reveal a consistent and pronounced increase in mean LST across all zones from 2000 to 2010, followed by a modest decline in all zones from 2010 to 2020. In 2000, mean LST values across zones ranged between 22.61°C and 23.60°C—remarkably uniform across the city. By 2010, mean LSTs had risen by between 13°C and 19°C depending on the zone, with

Table 3: Zone-wise Land Surface Temperature (LST) Statistics of Prayagraj City (2000–2020)

Zone	Year	Min LST (°C)	Mean LST (°C)	Max LST (°C)	Std. Dev.
Zone 1	2000	17.60	22.61	28.33	1.58
	2010	31.34	40.91	47.08	2.28
	2020	30.40	37.30	40.73	1.56
Zone 2	2000	19.25	22.87	26.82	0.88
	2010	30.51	39.47	46.38	2.16
	2020	28.56	37.99	41.19	1.55

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Zone 3	2000	19.43	22.64	27.75	0.92
	2010	30.44	39.11	44.78	2.17
	2020	30.90	37.39	41.39	1.47
Zone 4	2000	19.42	23.30	27.82	1.27
	2010	31.84	40.80	48.66	2.50
	2020	30.73	38.35	43.05	1.59
Zone 5	2000	16.82	23.44	29.65	1.52
	2010	30.71	40.22	50.01	2.80
	2020	27.23	35.79	44.62	1.86
Zone 6	2000	17.70	23.22	28.50	1.64
	2010	32.51	41.44	50.07	2.70
	2020	29.84	35.96	43.77	1.41
Zone 7	2000	19.39	23.06	27.83	1.36
	2010	29.80	36.93	45.96	2.89
	2020	29.73	35.80	41.03	1.56
Zone 8	2000	18.83	23.60	28.62	1.36
	2010	29.83	40.34	49.37	2.56
	2020	29.40	36.11	43.61	1.84

Source: Computed and prepared by the researcher using Landsat thermal imagery (2000, 2010, and 2020) through GIS and Remote Sensing techniques.

Zone 6 recording the highest mean (41.44°C) and Zone 7 the lowest (36.93°C). The 2020 values, while lower than 2010, remained markedly above 2000 levels in every zone, underscoring the lasting thermal legacy of the rapid urbanization of the preceding decade.

V.IV. RELATIONSHIP BETWEEN BUILT-UP AREA, NDVI AND LST

V.IV.I. IMPACT OF BUILT-UP EXPANSION ON VEGETATION COVER

The data presented in the preceding sections establish, with considerable empirical clarity, the inverse relationship between the expansion of built-up areas and the persistence of vegetative cover in Prayagraj. As total built-up area grew from 66.69 sq. km in 2000 to 197.81 sq. km in 2020, total vegetation area declined from 199.69 sq. km to 56.72 sq. km over the same period. The spatial coincidence of these trends—most dramatically evident in the peripheral zones (5, 6, 7, 8), where the most intensive urban growth occurred alongside the most precipitous vegetation losses—underscores the direct land competition between urban development and green cover.

The conversion of vegetated land to impervious built-up surfaces eliminates the ecosystem services provided by vegetation, including evapotranspirative cooling, carbon sequestration, surface water retention, and habitat provision. The loss of tree canopy and agricultural vegetation in Prayagraj's expanding periphery has had particularly far-reaching consequences for the thermal environment of the city, as examined in the following subsections.

V.IV.II. RELATIONSHIP BETWEEN NDBI AND LST

The relationship between NDBI and LST is well-established in the remote sensing literature: areas of high NDBI—dense built-up surfaces—are consistently associated with elevated LST values.[1] This relationship was clearly evident in the Prayagraj data. In 2010, the zones with the highest built-up growth rates (Zones 6, 7, 8) also recorded the largest absolute increases in mean LST from the 2000 baseline. Conversely, Zone 7, which began from the lowest built-up base in 2000, recorded the lowest mean LST in 2010. The strong positive correlation between NDBI and LST reflects the physical properties of built-up materials: concrete, asphalt, brick, and metal have high heat capacities and low albedos, causing them to absorb large quantities of solar radiation and re-radiate it as sensible heat. The resulting surface temperature elevations are further amplified by the reduction in latent heat flux—evapotranspiration—that accompanies the removal of vegetation.

V.IV.III. RELATIONSHIP BETWEEN NDVI AND LST

A well-documented negative relationship exists between NDVI and LST: zones with higher vegetation density tend to register lower surface temperatures, while areas of low NDVI are associated with elevated thermal readings.[2] This relationship was confirmed by the Prayagraj data. In 2000, when all zones still retained substantial vegetation (mean NDVI values ranging from 0.207 to 0.435), mean LST values were uniformly moderate (22.61°C–23.60°C). By 2010, the sharp drop in NDVI values across all zones—particularly in Zones 5, 6, 7, and 8—was mirrored by dramatic LST increases. The partial vegetation recovery between 2010 and 2020, documented in the NDVI analysis, was accompanied by moderate LST declines in most zones, further confirming the thermal mitigation potential of urban vegetation. This inverse NDVI–LST relationship has important policy implications: investment in urban greening, tree planting, and the protection of existing vegetation can yield measurable reductions in surface temperatures and contribute to the mitigation of urban heat stress.

V.IV.IV. INTERRELATIONSHIP AMONG NDBI, NDVI AND LST

The data from this study confirm the theoretically expected interrelationships among NDBI, NDVI, and LST in no uncertain terms. A strong positive relationship between NDBI and LST was evidenced by the consistent co-occurrence of high built-up density and elevated surface temperatures across zones and time periods.[3] Conversely, the negative relationship between NDVI and LST was confirmed by the inverse temporal trends—NDVI declining as LST rose from 2000 to 2010, and the partial LST recovery between 2010 and 2020 coinciding with partial NDVI recovery. Together, these three indices paint a coherent and empirically robust picture of the thermal consequences of Prayagraj's urban expansion: the replacement of vegetated land covers by impervious built-up surfaces has driven significant increases in surface temperature, transforming the thermal environment of the city and intensifying the Urban Heat Island effect across all eight zones.

[1]Rizwan, A. M., Dennis, L. Y., & Liu, C. (2008). A review on the generation, determination and mitigation of Urban Heat Island. Journal of Environmental Sciences, 20(1), 120–128.
[2]Imhoff, M. L., Zhang, P., Wolfe, R. E., & Bounoua, L. (2010). Remote sensing of the urban heat island effect across biomes in the continental USA. Remote Sensing of Environment, 114(3), 504–513.
[3]Patel, S., & Bhatt, R. (2020). Urbanization patterns and environmental impacts in mid-size Indian cities. Urban Climate, 32, 100594.

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V.IV.V. URBAN HEAT ISLAND EFFECT IN PRAYAGRAJ CITY

The Urban Heat Island (UHI) effect refers to the phenomenon by which the built-up core of an urban area records significantly higher temperatures than its rural or vegetated surroundings.[4] The LST data for Prayagraj provide compelling evidence for the development and intensification of UHI conditions within the city over the study period. In 2000, mean LST values were relatively uniform across zones (22.61°C–23.60°C), suggesting that thermal differentiation between the urban core and periphery was modest at that time. By 2010, however, a pronounced thermal gradient had emerged: the rapidly developing peripheral zones (6 and 8) recorded the highest mean temperatures (41.44°C and 40.34°C respectively), while the temperatures in all zones had elevated far above the 2000 baseline. This pattern suggests that urban heat intensity in Prayagraj's expanding frontier matched or exceeded that of the established urban core during the period of peak construction activity.

The 2020 data indicate a moderate easing of peak temperatures across most zones, though mean LSTs remained substantially elevated above 2000 levels. The standard deviation of LST—a measure of within-zone thermal variability—also showed generally lower values in 2020 compared to 2010, suggesting a degree of spatial temperature homogenization as urban development consolidated. The persistence of UHI conditions in Prayagraj, even amidst partial greening in the 2010–2020 decade, underscores the profound and lasting thermal legacy of rapid urban expansion and the urgent need for heat-mitigating planning strategies.

V.V. ENVIRONMENTAL IMPACTS OF URBAN GROWTH

The rapid urbanization of Prayagraj over the two decades from 2000 to 2020 has generated a complex array of environmental consequences that extend well beyond the thermal effects documented in the preceding analysis. These impacts, while interrelated, can be organized under the following thematic headings:

- Changes in Land Use and Land Cover: The conversion of agricultural fields, grasslands, riparian zones, and forests to built-up uses has fundamentally restructured Prayagraj's land use mosaic. The near-tripling of built-up area from 66.69 sq. km to 197.81 sq. km has been achieved at the direct expense of vegetated and open land covers, altering surface hydrology, reducing groundwater recharge, and disrupting the ecological connectivity of the landscape.
- Reduction of Vegetation and Green Spaces: The loss of 142.97 sq. km of vegetated area between 2000 and 2020—amounting to approximately 72% of the city's initial vegetation cover—has severely degraded the ecological fabric of the urban environment. The removal of forests, tree canopies, and agricultural vegetation has reduced the city's capacity for carbon sequestration, stormwater management, and biodiversity support, while simultaneously diminishing the aesthetic and recreational value of the urban landscape.
- Increase in Thermal Stress and Environmental Degradation: The dramatic rise in LST across all zones—from mean values of approximately 22°C–23°C in 2000 to 36°C–41°C in 2010, and to 35°C–38°C by 2020—has created conditions of severe thermal stress, particularly during the hot summer months. Elevated surface temperatures intensify urban heat stress, increase cooling energy demand, exacerbate air pollution through the acceleration of photochemical reactions, and adversely affect the health and productivity of urban residents.
- Impact on Ecological Sustainability: The combined effect of built-up expansion, vegetation loss, and thermal intensification has significantly diminished the ecological sustainability of Prayagraj's urban environment. The city's natural capital—its vegetated landscapes, riverine ecosystems, and open green spaces—is being depleted faster than it is being replenished, raising fundamental questions about the long-term sustainability of current urban development trajectories.

[4]Connors, J. P., Galletti, C. S., & Chow, W. T. (2013). Landscape configuration and urban heat island effects: Assessing the relationship between landscape characteristics and land surface temperature in Phoenix, Arizona. Landscape Ecology, 28(2), 271–283.

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VI. CONCLUSION

The present chapter has undertaken a systematic, zone-wise analysis of the growth of built-up areas, vegetation dynamics, and land surface temperature in Prayagraj city over the two decades from 2000 to 2020, using NDBI, NDVI, and LST indices derived from multi-temporal Landsat satellite imagery. The following major observations emerge from this comprehensive analysis.

First, Prayagraj has experienced exceptional built-up area growth over the study period, with total urban land cover nearly tripling from 66.69 sq. km to 197.81 sq. km. This expansion has been predominantly peripheral in character, with Zones 5, 6, 7, and 8 absorbing the largest absolute increments in built-up area. Areas such as Jhalwa, Mawaiya, Phaphamau, Transport Nagar, and Sanauti emerged as particularly dynamic growth nodes during the 2000–2020 period.

Second, this built-up expansion was accompanied by a dramatic and largely irreversible loss of vegetated land cover, with total city vegetation declining from 199.69 sq. km in 2000 to 44.49 sq. km in 2010—a loss of 77.72%—before a partial recovery to 56.72 sq. km by 2020. The peripheral zones that experienced the most intensive built-up growth also suffered the most severe vegetation losses, reflecting the direct land competition between urban development and green cover.

Third, land surface temperatures rose dramatically across all eight zones between 2000 and 2010, with mean LST increasing by 13°C–19°C over the decade. The spatial pattern of LST intensification closely tracked the geography of built-up expansion and vegetation loss, confirming the strong positive NDBI–LST and negative NDVI–LST relationships. A moderate LST decline was observed between 2010 and 2020, coinciding with partial vegetation recovery, though temperatures remained far above 2000 levels in every zone, attesting to the lasting thermal impact of rapid urbanization.

Fourth, the combined evidence from NDBI, NDVI, and LST analyses confirms the development and intensification of Urban Heat Island conditions across Prayagraj city, with all zones experiencing significant surface temperature elevations relative to the 2000 baseline. The thermal stress now prevalent across the city poses serious risks to public health, energy demand, and the quality of the urban living environment.

In conclusion, the rapid and spatially extensive urbanization of Prayagraj between 2000 and 2020 has produced a major restructuring of the city's land cover, thermal environment, and ecological character. Addressing these challenges will require a concerted shift towards sustainable urban planning approaches that prioritize the integration of green infrastructure into new development, the protection of existing natural vegetation, the promotion of energy-efficient and thermally reflective building designs, and the active management of urban tree canopy. Instruments such as mandatory green cover ratios in development approvals, tree replacement policies, green belt designations, and urban forestry programmes must be integrated into Prayagraj's planning framework as a matter of urgency, if the city is to mitigate the thermal and ecological costs of its rapid growth and chart a more sustainable trajectory for the future.:

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