Climate Change Vulnerability Assessment of Heat Stress in Major Urban Centers in Bihar: PMC

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Patna Municipal Corporation

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Executive Summary

A heatwave, characterized by prolonged periods of exceptionally high temperatures, poses a significant threat to urban populations, particularly in cities like Patna. Occurring mainly from April to June, heatwaves in Patna have intensified due to rapid urbanization and climate change, leading to increased health risks, mortality rates, and economic burdens. In recent years, peak temperatures have consistently exceeded 40°C, with alarming humidity levels further exacerbating the situation. This study aims to analyze the rising frequency and severity of heatwaves in Patna, drawing on a rich dataset of climatological, demographic, and socioeconomic information. The primary objective is to assess the implications of rising temperatures on Patna's urban population. A robust methodology has been implemented, involving the analysis of satellite imagery, meteorological records, and demographic statistics. This comprehensive approach allows for a thorough examination of heatwave patterns and their impacts on the community.

Recent data indicates a worrying trend of increasing temperatures in Patna, with maximum temperatures rising at a rate of 0.10°C per decade and minimum temperatures by 0.18°C. The most extreme temperature recorded in 2024 reached a staggering 48.2°C, underscoring the urgency of addressing heat-related vulnerabilities in the city, particularly as the population continues to grow, currently standing at 1,684,297, with a significant portion being of working age (42.87%). A pivotal aspect of this study involves identifying thermal hotspots within the urban landscape of Patna. By utilizing a percentile method based on temperature data, areas experiencing temperatures above the 95th percentile are delineated. The resultant thermal hotspot maps reveal significant spatial disparities, highlighting wards where residents face heightened physiological and socioeconomic risks due to extreme heat. Findings indicate that certain wards, particularly 3, 22, and 56, are at the highest risk, characterized by dense urban environments contributing to the urban heat island effect, exacerbating temperature disparities across the city.

The exposure analysis focuses on critical community assets, including population density, land use, and surface temperature. Using a combination of the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI), the study assesses how different land cover types influence temperature dynamics. Findings reveal that wards dominated by impervious surfaces, such as concrete and asphalt, consistently show higher Land Surface Temperatures (LST), leading to increased heat stress for residents. The analysis quantifies vulnerability across different wards, identifying Ward 3 as the most exposed, with an exposure score of 48.41, primarily due to significant urban growth. In contrast, Ward 9, despite having a lower population density, exhibits

high exposure due to its extensive built environment. The study illustrates that infrastructure and land use significantly contribute to heat vulnerability, irrespective of population density.

In response to these findings, the study presents actionable recommendations aimed at enhancing heat resilience in Patna. Key strategies include increasing urban green spaces, which can mitigate heat absorption and improve air quality; improving urban planning by integrating sustainable design principles into development; and conducting public awareness campaigns to educate residents about heat risks and preventive measures. Additionally, developing city-wide emergency response protocols, including timely alerts and access to cooling centers, can protect vulnerable populations during extreme heat events. Infrastructure improvements, such as implementing cool roofs and reflective materials, can significantly lower surface temperatures and improve the urban climate.

This comprehensive heat study equips policymakers, urban planners, and community stakeholders with essential insights to bolster heat resilience in Patna. By addressing critical factors contributing to heat vulnerability, this research aims to safeguard public health and well-being, fostering sustainable urban growth amidst the challenges posed by climate change. The findings underscore the importance of coordinated efforts among local authorities, health departments, and community organizations to mitigate heatwave impacts effectively. Through targeted interventions and proactive measures, Patna can enhance its resilience to heatwaves, ultimately protecting its residents and promoting a healthier urban environment. This study also relies on secondary data, including demographic profiles, daily meteorological records, and historical evidence of heatwave impacts, providing a solid foundation for future research and policy development. As the frequency of extreme heat days increases, particularly since 2010, it is imperative for local authorities to implement the recommendations outlined in this report to ensure the well-being of Patna's urban population.

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1 Introduction

Patna, the capital city of Bihar, is situated along the southern bank of the River Ganges, extending 15 km along its course. Positioned between the humid West Bengal to the east and the sub-humid Uttar Pradesh to the west, Patna enjoys a transitional climate that reflects both regions' economic and cultural influences. The city is surrounded by three rivers—Ganga, Sone, and Punpun—while the Gandak River merges with the Ganges nearby, making Patna a unique confluence point. The Mahatma Gandhi Setu, stretching 5575 meters across the Ganges, connects Patna to Hajipur and is India's longest river bridge. As a gateway to prominent Buddhist and Jain pilgrimage sites like Vaishali, Nalanda, and Bodhgaya, Patna holds spiritual significance alongside its economic and political importance[1].

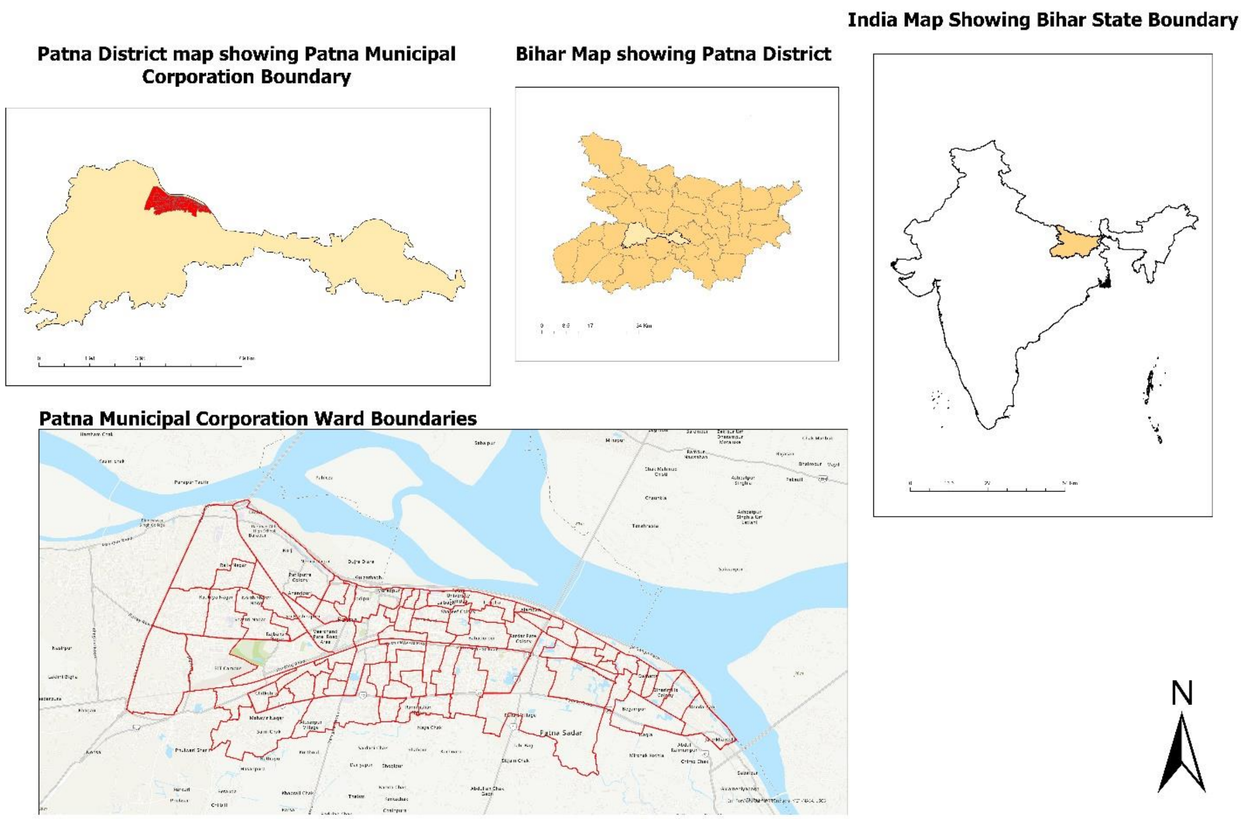

Figure 1 - Study Area

[1] Patna: City Profile , Rakesh Tiwari and Nikita Sharma ,Poverty, Inequality and Violence in Urban India: Towards Inclusive Planning and Policies, Institute for Human Development, New Delhi 2016

Patna Municipal Corporation (PMC), Patna is the most populous growing city in India, and it is the headquarters of Patna district and the capital of Bihar state. The area is located on the southern bank of the river Ganga at a Latitude between 25° 33’22’’N to 25°39’20’’N and a Longitude between 85°04’50’’E to 85°16’03.55’’E. The study area exists in SOI toposheet nos. 72G/2 & 72G/6. Physiographically the topography of the study area is flat, and a part of the alluvial floodplain deposits part of the Ganga basin at the height of 53 m/ 173 feet above MSL: Figure 1 show the location of the study area. The total area of PMC, Patna, is 109.218 sq. km[2]. The total population of PMC, Patna is 16, 87,828 as per the 2011 census with its seventy-two wards, as per 2011 census[3]. It serves as the primary political and financial center in Bihar, accounting for a significant share of the state's urban population. Patna Municipal Corporation (PMC) governs the city, managing 44.1% of the population across Bihar's seven municipal corporations. PMC oversees various urban services, playing a vital role in addressing the challenges brought by Patna's rapid growth. The city, with a population now exceeding 2 million, is among the fastest-growing in India but struggles with infrastructure gaps, traffic, and environmental degradation.

1.1 Heatwave in Patna

During the period 1975 to 2004 Patna experienced moderate heat wave conditions of short spell (3-4 days) except in 1975 (7-14 June), 1979 (1-8 June), 1992 (1-6 June) and 1998 (6-14 June). Highest maximum temperature recorded was 46.1º C on 16th June, 1995.[4] For Patna station, there is increasing trend in moderate, severe and total heat waves but are statistically non-significant.[5] The heatwave forced the Patna district administration to extend schools summer vacation until June 30.[6]

The heatwave in Patna has been particularly severe in 2024, with temperatures consistently exceeding 42 degrees Celsius and reaching as high as 48.2 degrees Celsius in some districts.[7] The India Meteorological Department (IMD) issued multiple heatwave alerts, including a red alert for extreme conditions affecting several districts. Tragically, the heatwave has resulted in fatalities;

[2]Ahmad M. Y., Munim N. H. 2020. Approach of Remote Sensing and GIS Techniques of Land Use and Land Cover Mapping -Patna Municipal Corporation, (PMC) Patna, Bihar, India. Current World Environ 15(2). DOI: http://dx.doi.org/10.12944/CWE.15.2.25

[3] Census of India. 2011. District Census Handbook, New Delhi, Director of Census Operations Bihar. https://censusindia.gov.in/2011census/dchb/DCHB_A/ 10/1028_PART_A_DCHB_PATNA.pdf. Published 2011. Accessed December 16, 2018.

[4] A study of heat wave/ severe heat wave over Bihar and Jharkhand

[5] Climatic variability and extreme weather events in Bihar https://doi.org/10.54386/jam.v19i1.767

[6] https://ikcest-drr.osgeo.cn/static/upload/27/2792e640-3670-11ea-a54b-00163e0618d6.pdf

[7]https://timesofindia.indiatimes.com/city/patna/11-dists-in-grip-of-severe-heatwave-abad-breaks-own-record-at-48-2c/articleshow/110547380.cms

reports indicate that at least eight people have died due to heat-related illnesses, including a police official[8]. Additionally, over 100 students fainted in schools across the region, necessitating medical attention[9]. In response to the extreme heat, the Patna district administration extended school closures for students up to class 8 until June 22[10], highlighting the ongoing public health crisis. The situation has been exacerbated by high humidity levels, which have made conditions even more unbearable for residents throughout the state. A study by *The Energy and Resources Institute (TERI)*[11] suggests that Patna could experience up to a 30% increase in the number of heatwave days by 2050 if global emissions are not significantly reduced.

1.2 Climatology of Patna Municipal corporation

Patna's climatological data from 1981 to 2023 reveals notable seasonal variations in temperature and humidity. January, the coldest month, sees average high temperatures of 23.31°C and minimum temperatures around 10.09°C[12]. In contrast, May, the hottest month, records average maximum temperatures of 37.93°C. The summer months, particularly from March to June, are characterized by consistently high temperatures, often exceeding 30°C, with May being the peak heat period.

The climate in Patna is classified as tropical, featuring distinct wet and dry seasons. The wet season, which lasts from June to September, is typically hot, humid, and overcast, while the dry season from October to May is warm and predominantly clear[13]. During the summer, temperatures often exceed 40°C, especially between April and June. Conversely, winter temperatures range from 10°C to 15°C in December and January.

Rainfall is concentrated during the monsoon season, with July being the wettest month, averaging approximately 186 mm of precipitation[14]. Humidity levels are notably high during this period, often exceeding 80%, which can lead to oppressive conditions. Relative humidity at maximum temperatures is particularly low during the pre-monsoon months of March and April, measuring around 26.71% and 25.25%, respectively. In contrast, during the monsoon months of July and August, humidity levels rise significantly, peaking at around 69.21% and 65.87%, resulting in a

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[8] https://www.downtoearth.org.in/environment/heatwave-and-hot-winds-claim-two-lives-in-bihar-95770
[9] https://www.downtoearth.org.in/climate-change/scorching-days-sweltering-nights-bihars-heatwave-impact-worsens-due-to-hot-nights
[10] https://www.downtoearth.org.in/climate-change/scorching-days-sweltering-nights-bihars-heatwave-impact-worsens-due-to-hot-nights
[11] https://www.teriin.org/article/heat-waves-and-action-plans-how-does-india-fare
[12] https://www.climatechip.org/your-area-climate-data
[13] https://imdpune.gov.in/library/public/Climate%20of%20Bihar.pdf
[14] SINGH, VIVEKANAND & SINGH, ANSHUMAN. (2017). Variation of temperature and rainfall at Patna. Mausam. 68. 161-168. 10.54302/mausam.v68i1.445.

muggy atmosphere. Wind speeds in Patna exhibit seasonal variation, with the windiest months occurring between February and September, peaking in June at an average speed of approximately 8.5 km/h[15]. Winds generally blow from the east during summer but shift to the west in winter. This climatic profile emphasizes Patna's humid subtropical climate characterized by hot summers, heavy monsoon rains, and mild winters. The extremes in temperature and high humidity during the monsoon present challenges regarding comfort and health, alongside risks related to flooding and other weather-related issues.

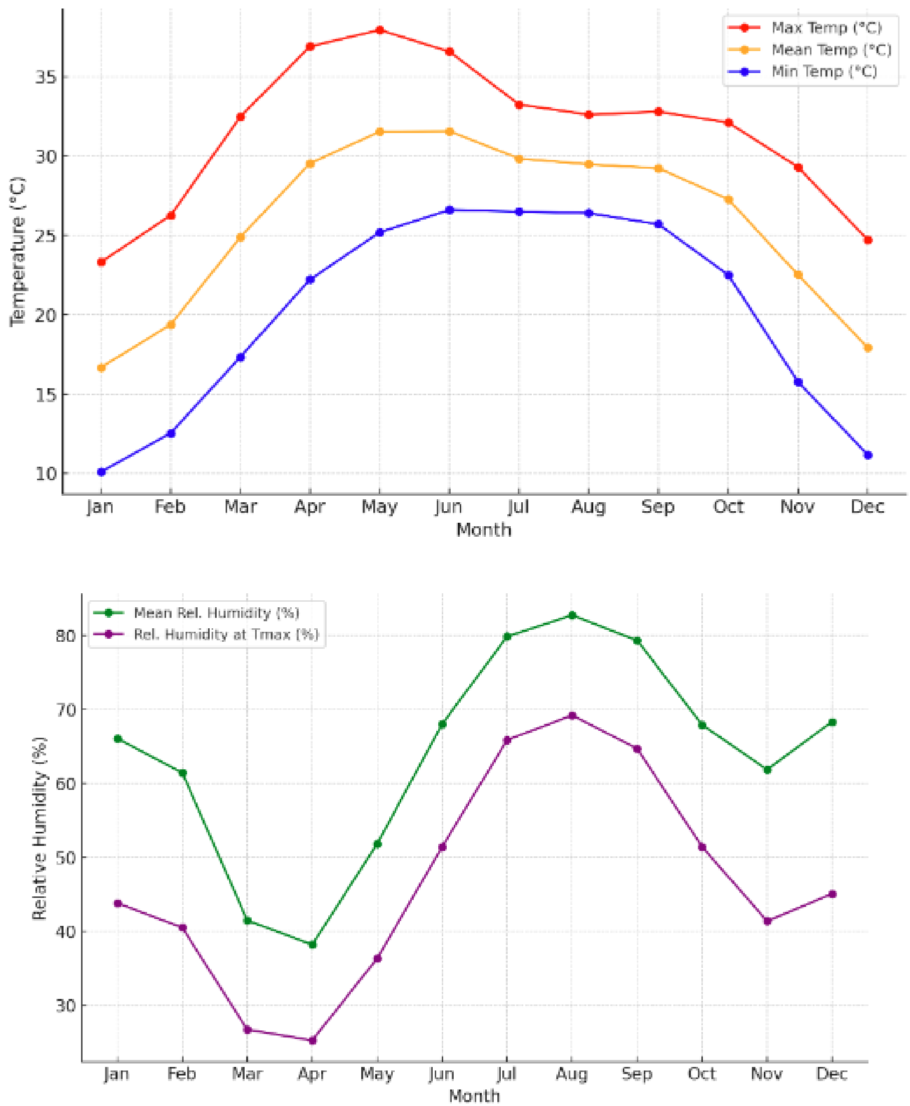


Figure 2- Monthly Temperature and Relative Humidity for Patna

[15] Climate Report of Patna: https://www.scribd.com/document/529411345/Climate-Report-of-Patna

1.3 Demography

As per the 2011 Census, the total population of Patna Municipal Corporation stood at 1,684,297. The largest portion of the population falls within the working-age group of 25-59 years, representing 42.87% of the total, followed by the 0-14 years age group, which makes up 28.96%. The senior population, those above 60 years, constitutes the smallest group at 7.97%. This demographic distribution reflects Patna's role as an important urban center with a significant working-age and youth population.

Based on the ward-wise population data of Patna Municipal Corporation, Ward 22 is the most populated, housing 5.95% of the total population with 100,261 residents and 18,861 households. It is followed by Ward 31, which accounts for 2.36% of the population with 39,768 residents and 6,881 households, and Ward 30, which holds 2.34% with 39,347 residents and 6,594 households. In contrast, the least populated wards include Ward 23 with 0.52% of the population (8,769 residents), Ward 9 with 0.69%, and Ward 39 with 0.65%. The most densely populated area and household size are shown in Figure 3 below.

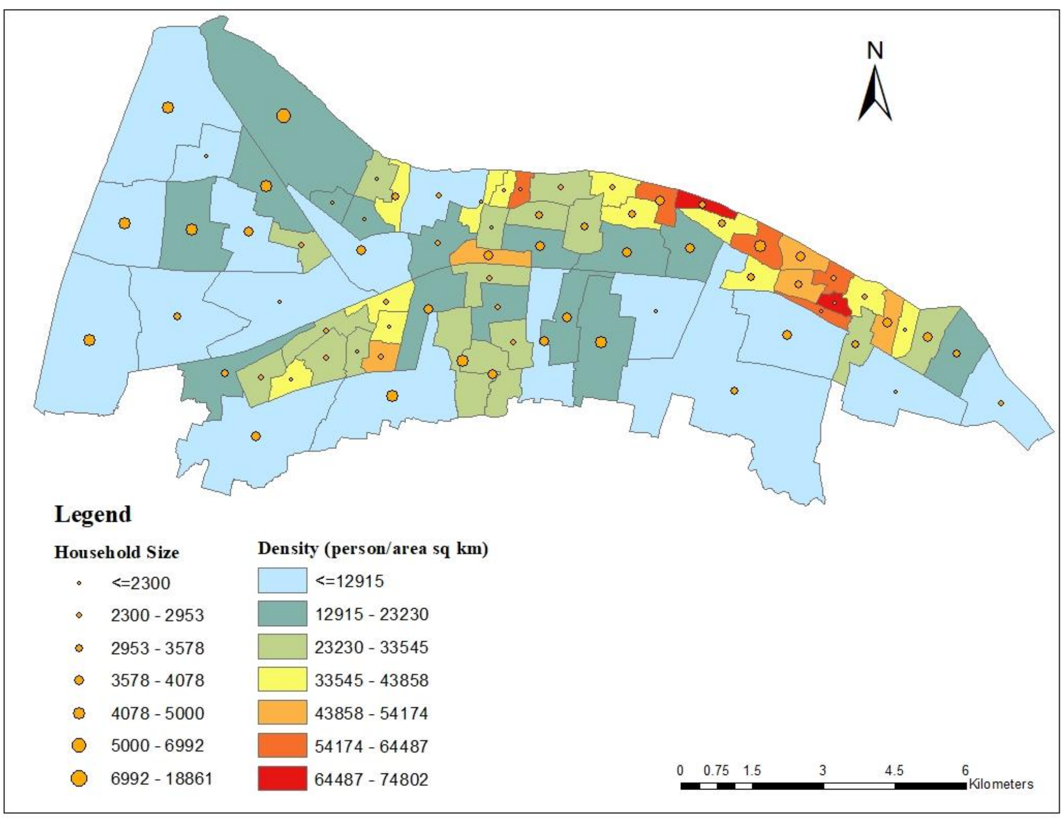


Figure 3- Population Density and Household size of Patna Municipal Corporation

1.4 Socioeconomic characteristics

The social, economic, and demographic attributes of Patna Municipal Corporation reflect directly on the social vulnerability of the city. Social exclusion or deprivation and urban poverty are some of the major social issues in PMC.

In Patna Municipal Corporation, the employment landscape is dominated by the service sector, with the highest worker involvement, followed by the secondary sector (manufacturing and construction) and the primary sector (agriculture). The five largest employment sectors are transport, storage, and communication, which employs 26.5% of the workforce, manufacturing at 22.0%, public administration, education, health, and other services at 19.0%, trade, hotels, and restaurants at 17.4%, and agriculture at 7.5% as shown in figure 4. This distribution reflects Patna's status as a growing urban hub, with a diverse range of economic activities supporting its workforce.

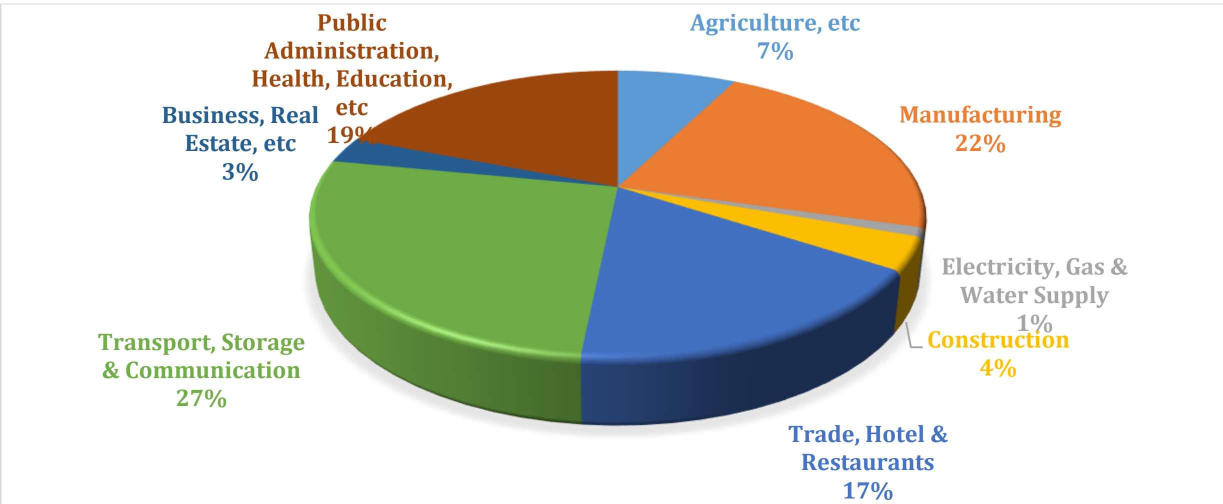


Figure 4- Distribution of workers by industry

The gender distribution of employment shows in figure 5 that females are predominantly concentrated in public administration, education, and health, with 54.7% of women employed in this sector. This is followed by manufacturing, where 21.2% of women work, and agriculture, which engages 17.3%. These sectors provide crucial formal and informal employment opportunities for women, particularly in education, healthcare, and public services, where there is a strong demand for skilled and semi-skilled labor. For men, the occupational structure is different, with the largest share, 29.2%, employed in the transport, storage, and communication sector, which includes jobs such as drivers, logistics, and delivery services. Manufacturing is the second largest sector for men, employing 22.1%, while trade, hotels, and restaurants follow, engaging 18.8% of the male workforce.

This highlights men's dominance in sectors requiring physical labor and technical skills, reflecting the broader trend of male employment in industrial and commercial activities in Patna's urban economy.

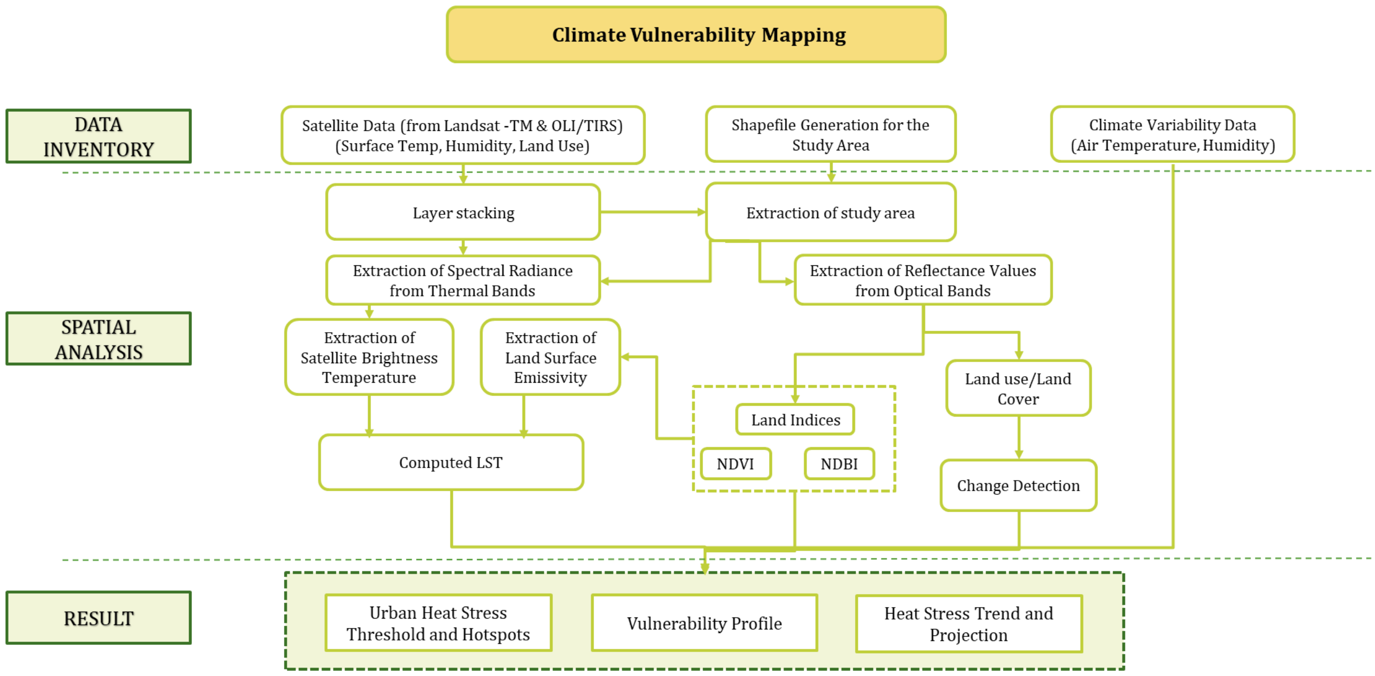
Figure 5- Gender Distribution of workers across major occupation

Source: Unit level data from NSSO, 61st and 68th Rounds

1.5 Approach and tools

1.5.1 Methodology

This study has been initiated by investigating secondary information such as demography and socioeconomic data, past studies on heatwaves and their impacts, to understand the local context in Patna. Daily meteorological data on climate variables (temperature and humidity) over the last 24 years for Patna Municipal Corporation have been analyzed for trend analysis. Likewise, satellite images and remote sensing data have been investigated using GIS tools for extreme events. The research on historical evidence of heatwave impacts in the study area has been done through literature review and newspaper articles. Some of the critical steps for this initiative are heat hotspot and exposure underlying factors for the heatwave impacts), and identification of vulnerable groups. Finally, heat thresholds and hotspots are identified by investigating the above-mentioned processes and tools, which provide information on when and where to act in relation to extreme heat days.



1.5.2 Data Used

The data used for the study area analysis are

i. Landsat 5 thematic mapper images for the year 1994, 2004

ii. Landsat 8 OLI/TIRS images for 2014, 2023 (Source: https://earthexplorer.usgs.gov).

iii. Temperature and Humidity Data (Source- NOAA/GSOD (US National Oceanographic and Atmospheric Administration/ Global Summary of the Day)).

iv. Socio Economic dataset (Census of India, 2011)

v. Google Earth Images for reference (source: Google Earth Pro)

vi. Patna Municipal Corporation urban boundary ma.

vii. ArcGIS 10.8 For Preparation of LST and LULC maps. The details about the Landsat images are given in Table-1

Table 1: Data Used

Satellite (Sensor)/Ancillary Data	Path/Row	Resolution / Scale	Acquisition Date	Constants of Thermal Coefficient		Source
				K_1	K_2	
Landsat-5 (TM)	141/42	30m	19-03-1994	607.76 (Band 6)	1260.56 (Band 6)	United States Geological Survey (USGS) web portal (https://earthexplorer.usgs.gov)
			04-04-1994			
			11-05-1994			
			07-06-1994			
			30-03-2004			
			15-04-2004			

			01-05-2004			
			02-06-2004			
Landsat-8 (OLI/TIRS)	141/42	30m	26-03-2014	774.8853 (Band 10)	1321.0789 (Band 10)	
			27-04-2014			
			13-05-2014			
			14-06-2014			
			27-03-2023			
			20-04-2023			
			14-05-2023			
			07-06-2023			
Temperature/Humidity dataset	-	0.5° x 0.5°	-	-	-	NOAA/GSOD (US National Oceanographic and Atmospheric Administration/ Global Summary of the Day)
Socio-economic dataset	-	-	-	-	-	Census of India, 2011
Ward Boundary Map	-	-	-	-	-	Patna Municipal Corporation

1.5.3 Data Processing

1.5.3.1 Image Pre-processing

The satellite imageries used in this study were downloaded from the USGS site for different periods. The digital boundaries are created in ArcGIS[16] (Khan et al., 2021) for processing further data. To obtain better results, the raster bands are pre-processed in ArcGIS software and image enhancement, atmospheric correction, removal of dark boundary and combining of different bands of images are done; this process is implemented for all the years. After successful pre-processing of satellite imageries, the area of interest is clipped for both the years, clipping reduces the image size.

1.5.3.2 Classification

The classification of all the images is performed in ArcGIS 10.8 using spatial analyst tool and maximum likelihood method of classification. The supervised classification method was selected for performing land use classification, in this method user trained the algorithm about different classes areas, this process is known as training sample which instruct the software to perform classification based on the trained samples. For classification, five classes are made (1) Agriculture, (2) Vegetation, (3) Built-up, (4) barren land (5) water bodies.

[16] Khan, F., Das, B., Ram Krishna Mishra, S., & Awasthy, M. (2021). A review on the Feasibility and Application of Geospatial Techniques in Geotechnical Engineering Field. Materials Today: Proceedings. https://doi.org/https://doi.org/10.1016/j.matpr.2021.02.108

1.5.3.3 Land Surface Temperature (LST)

The classified image of the study area is then used for the determination of LST. The LST map is generated using thermal band 6 for Landsat 5 and band 10, for Landsat 8[17] . The process is divided into 3 stages. The first stage involves the use of TIRS data and Band 10, the second stage involves the use of OLI data and Bands 4 & 5, while the third stage involves the use of the LST equation which includes variables from both stages to calculate LST itself.

The method flowchart is presented in Figure and steps to be followed under each stage are detailed in the following text

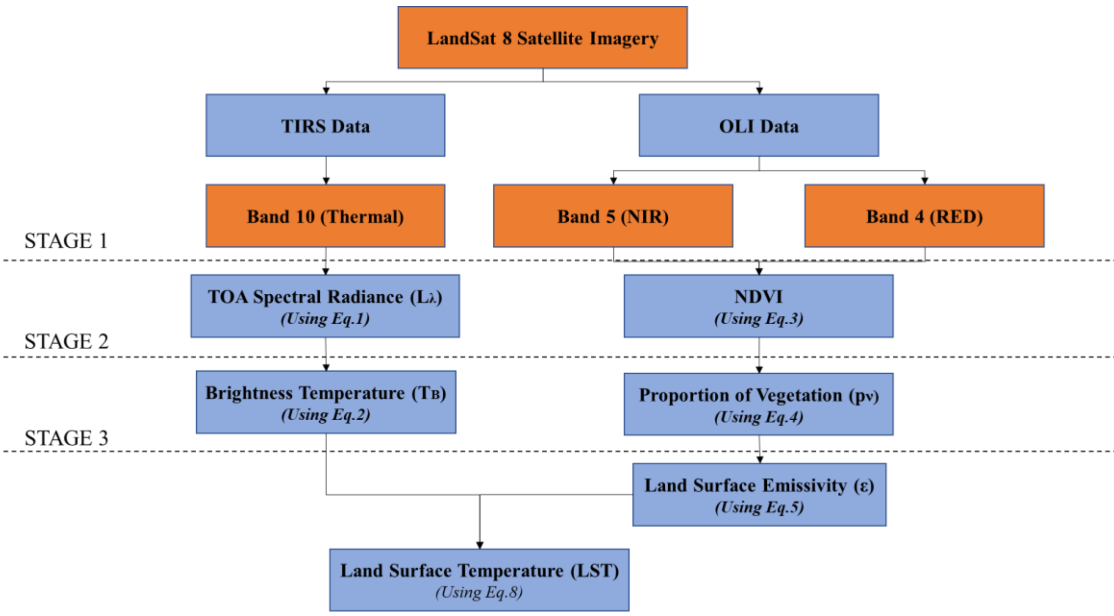


Figure 6- Methodology for LST retrieval from Landsat 8

STAGE 1

Thermal Infrared Sensor (TIRS) Data from the LandSat 8 image

1. Select Band 10 raster which records reflected light in the Thermal Infrared wavelength range.
2. Calculate the Top of Atmosphere (TOA) Spectral Radiance (in $Wm^{-2}sr^{-1}mm^{-1}$) which is the amount of reflected light being recorded by the satellite sensor. It is calculated using the equation below.

[17] Guha, Subhanil & Govil, Himanshu & Dey, Anindita & Gill, Neetu. (2018). Analytical study of land surface temperature with NDVI and NDBI using Landsat 8 OLI and TIRS data in Florence and Naples city, Italy. European Journal of Remote Sensing. 51. 667-678. 10.1080/22797254.2018.1474494.

$$L\lambda = 0.0003342 \times DN + 0.1 \qquad \text{Eq.1}$$

Where, DN is the digital number value for the quantized and calibrated standard product pixel of band 10 and 0.0003342 and 0.1 are the constants.

3. Calculate the Brightness Temperature which is the radiance of the microwave radiation travelling upward from the top of the atmosphere to the satellite. The equation is as follows and uses the spectral radiance calculated above:

$$T_n = \frac{K_2}{\ln\left(\left(\frac{K_1}{L\lambda}\right)+1\right)} \qquad \text{Eq.2}$$

Where, K1 and K2 are the calibration constants.

STAGE 2

Operational Land Imager (OLI) data from the LandSat image

1. Select Band 4 and Band 5 in LandSat 8 satellite image which record the reflected light in the red and near-infrared wavelength ranges respectively.
2. Calculate the Normalised Difference Vegetation Index (NDVI) from these two bands. NDVI is a ratio that ranges from -1 to 1 with higher values indicating higher vegetation, values close to 0 indicating barren land and negative values indicating water bodies. The equation to calculate NDVI is as follows

$$NDVI = \frac{(NIR-Red)}{(NIR+Red)} \qquad \text{Eq.3}$$

Where, NIR and Red are Band 5 and Band 4 of the Landsat 8 imagery respectively.

3. The next step is to calculate the Proportion of Vegetation as follows:

$$Pv = \left[\frac{NDVI-NDVI_{min}}{NDVI_{max-}NDVI_{min}}\right]^2 \qquad \text{Eq.4}$$

Where, NDVI is the Normalised Difference Vegetation Index from Eq. (3), NDVImin and NDVImax is the minimum and maximum NDVI of the Landsat scene respectively.

The normalized difference vegetation index (NDVI) is a simple graphical indicator that can be used to analyse remote sensing measurements, often from a space platform, assessing whether or not the target being observed contains live green vegetation.

4. Land Surface Emissivity is calculated using the equation

$$\varepsilon = 0.004 \times Pv + 0.986 \quad \text{Eq.5}$$

Where, Pv is the proportion of vegetation from Eq. (4)

STAGE 3

Getting the final Land Surface Temperature (LST) raster

1. The final LST is calculated using the equation:

$$LST = \frac{T_B}{1+(\frac{\lambda \sigma T_B}{hc}) ln\varepsilon} \quad \text{Eq.6}$$

   Where, λ is the effective wavelength (10.9 mm for band 10 in LandSat 8 data), σ is Boltzmann constant (1.38 × 10−23 J/K), h is Plank's constant (6.626 × 10−34 Js), c is the velocity of light in vacuum (2.998 × 10−8 m/sec), T_B is brightness temperature from Eq. (2) and ε is emissivity from Eq. (5).

2. This value of LST can be converted from Kelvin (K) to degree Celsius (°C) using the equation:

$$LST(°C) = LST(K) - 273.15 \quad \text{Eq.7}$$

2 Extreme Temperature

2.1 Heatwave definition

Heat waves do not have a global definition. The World Meteorological Organization (WMO) characterises a heat wave as "Five or more consecutive days of prolonged heat in which the daily maximum temperature is higher than the average maximum temperature by 5°C (9°F)." However, the definition and criteria for gauging temperature extremes vary significantly worldwide, tailored to local conditions based on climatological and impact criteria specific to each region.[18][19][20] The US, for example, adopts a complex felt temperature criterion that incorporates humidity with temperature, while Denmark utilizes a straightforward daytime maximum temperature threshold of 28°C. On the other hand, countries such as China and Brazil employ a percentile-based approach for

[18] World Meteorological Organization (WMO). 2012. "WMO Statement on the Status of the Global Climate in 2011."

[19] Alexander, Lisa V., X. Zhang, T. C. Peterson, J. Caesar, B. Gleason, A. M.G. Klein Tank, M. Haylock, et al. 2006. "Global Observed Changes in Daily Climate Extremes of Temperature and Precipitation." *Journal of Geophysical Research* 111 (D5): D05109. https://doi.org/10.1029/2005JD006290.

[20] Vose, Russell S., David R. Easterling, and Byron Gleason. 2005. "Maximum and Minimum Temperature Trends for the Globe: An Update through 2004." *Geophysical Research Letters* 32, no. 23: 1–5. https://doi.org/10.1029/2005GL024379.

measuring heat waves. In India, the India Meteorological Department (IMD) follows layered criteria for measuring heat waves

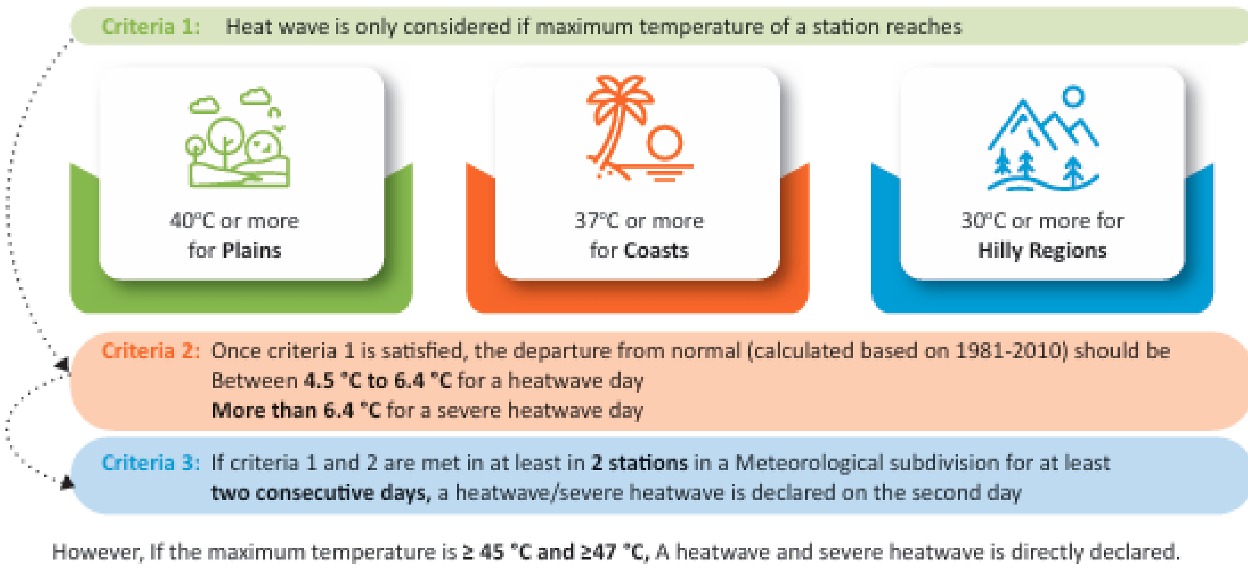


Figure 7- Criteria for mapping heat waves in India

Source: India Meteorological Department 2019

2.2 Heat Threshold Temperature

The maximum temperature data has been analysed to identify the threshold temperature. Figure 8 and 9 below shows the variation of annual extreme temperature in the past 43 years. The comparison between maximum and minimum temperatures in Patna Municipal Corporation from 1981 to 2023 reveals significant patterns. Maximum temperatures generally exhibit higher variability, with recorded values ranging from 30.99°C in 1981 to 32.4°C in 2023, indicating notable heat events. In contrast, minimum temperatures display a more stable trend, fluctuating between 19.37°C in 1983 and 20.99°C in 2023, suggesting less extreme variability compared to maximum temperatures.

While both maximum and minimum temperatures have shown upward trends—0.10°C and 0.18°C per decade, respectively—the increase in minimum temperatures is slightly more pronounced. This suggests that nighttime temperatures are rising at a faster rate than daytime temperatures, which can impact the diurnal temperature range. The narrowing of this range may lead to discomfort during warmer nights, affecting human health and well-being.

By the end of the 21st century, adults in the warmest regions are expected to experience approximately 3 additional nights of short sleep per year due to rising nighttime temperatures under the more moderate (RCP 4.5) scenario compared with upwards of 7 additional nights of short sleep under (RCP 8.5) scenario[21]. The relative mortality risk on days with hot nights could be 50% higher than on days with non-hot nights[22]. Overall, the observed trends indicate that while maximum temperatures are peaking more frequently, the increasing minimum temperatures may contribute to prolonged heat stress, emphasizing the need for targeted strategies to mitigate the effects of rising temperatures in urban environments like Patna.

Considering the heatwave definition by IMD, the figure 10 shows a significant year-to-year variation in the number of heat wave (HW) days from 1980 to 2023. In 1980, the number of heatwave days stood at 21, with notable variations in subsequent years. The data shows peaks, such as in 1995 with 32 heatwave days and 2012 with 33 days, indicating particularly extreme heat events. Conversely, there are years with minimal occurrences, such as 2020, which recorded no heatwave days. Despite this variability, there is a slight upward trend, with HW days increasing by approximately 0.07 days per year on average, suggesting a gradual rise in heat wave occurrences over time.

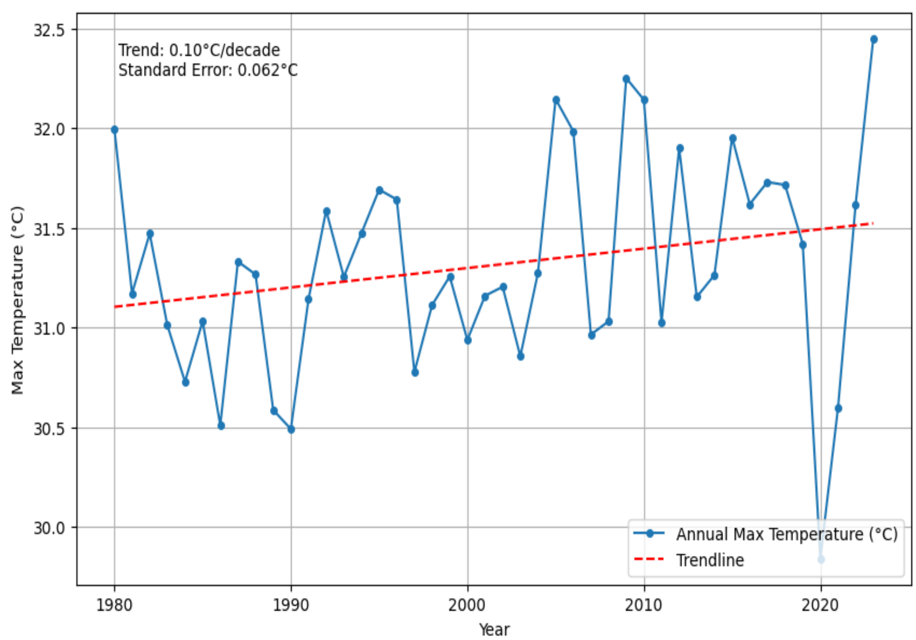


Figure 8- Annual Maximum Temperature Trend Analysis

[21] Minor, K et.al. (2022). Rising temperatures erode human sleep globally. One Earth, 5(5), 534-549.
[22] He, C et.al. (2022). The effects of night-time warming on mortality burden under future climate change scenarios: A modelling study. The Lancet Planetary Health, 6(8), e648-e657

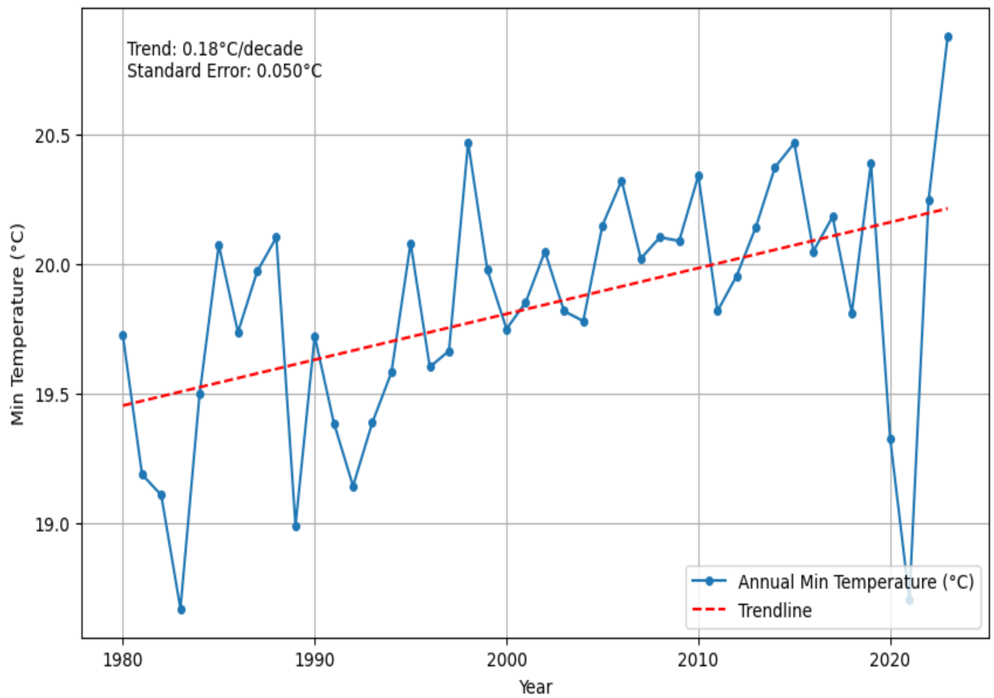


Figure 9- Annual Minimum Temperature Trend Analysis

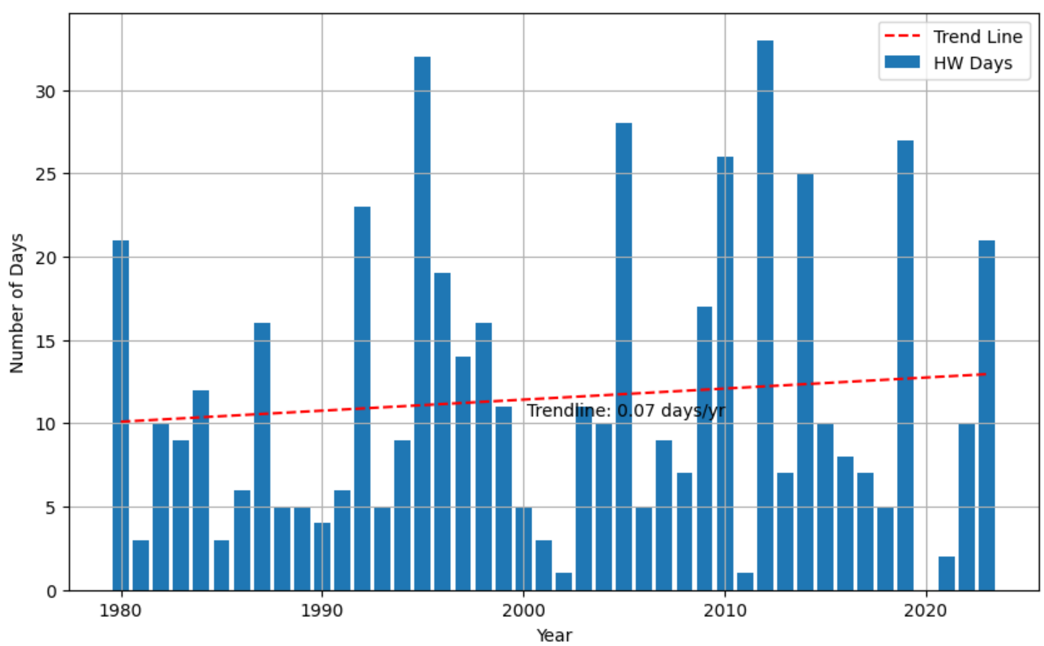


Figure 10- Heat Wave Days year-wise

2.3 Regression statistics of daily temperature derived from NOAA and ground measurements

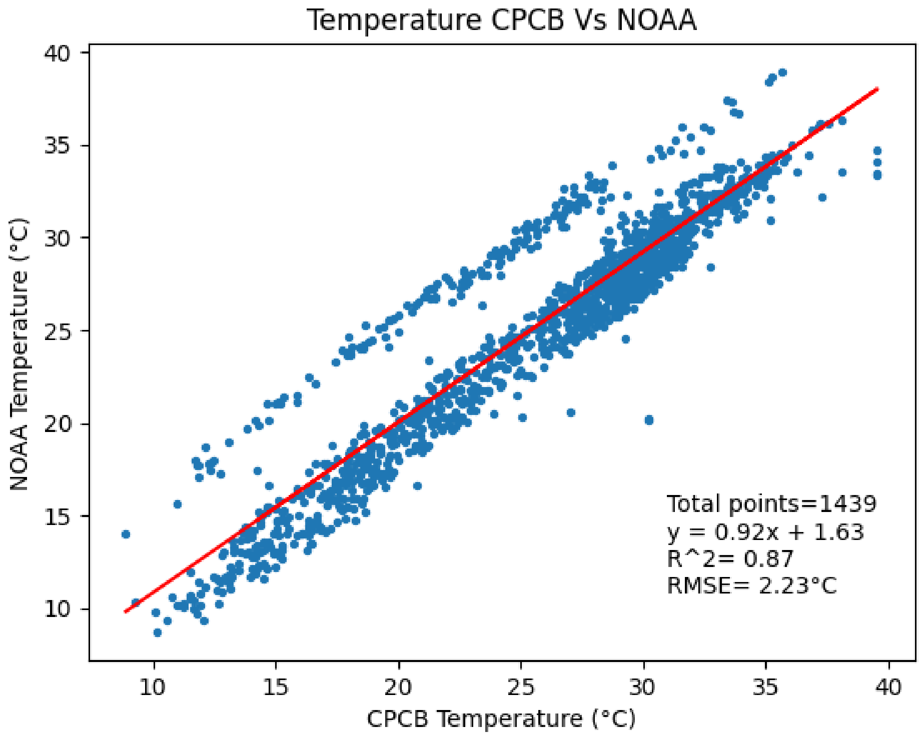


Figure 11- Regression statistics of temperature from NOAA and CPCB measurement

There is a strong positive correlation between CPCB and NOAA temperature measurements, as indicated by the clustering of data points along the trend line. The R^2 value of 0.87 indicates that 87% of the variability in NOAA temperatures can be explained by CPCB temperatures, demonstrating a high degree of linear correlation. RMSE of 2.23°C suggests that the average deviation of the observed temperatures from the predicted temperatures is relatively small, indicating good accuracy of the model.

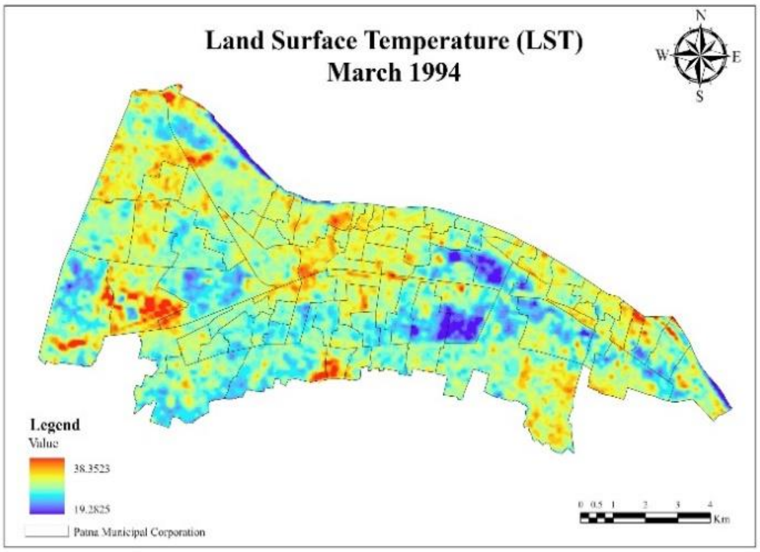
3 Spatial and Temporal variation in Patna Municipal Corporation

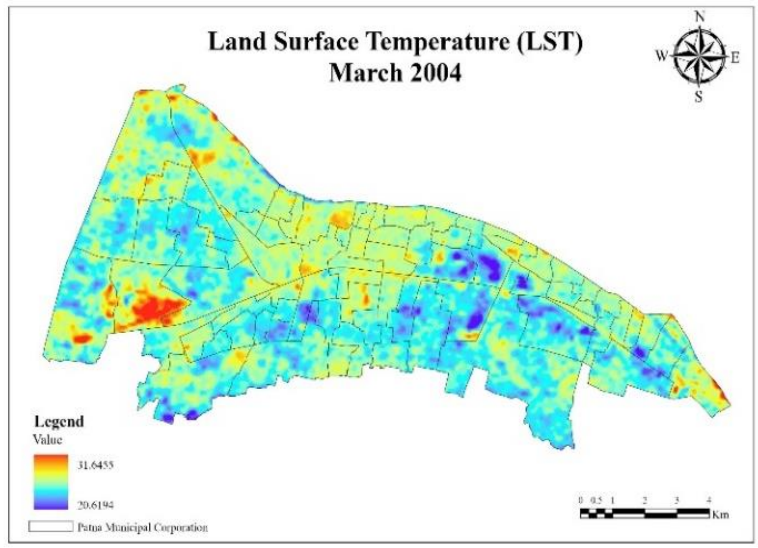
3.1 Land Surface Temperature

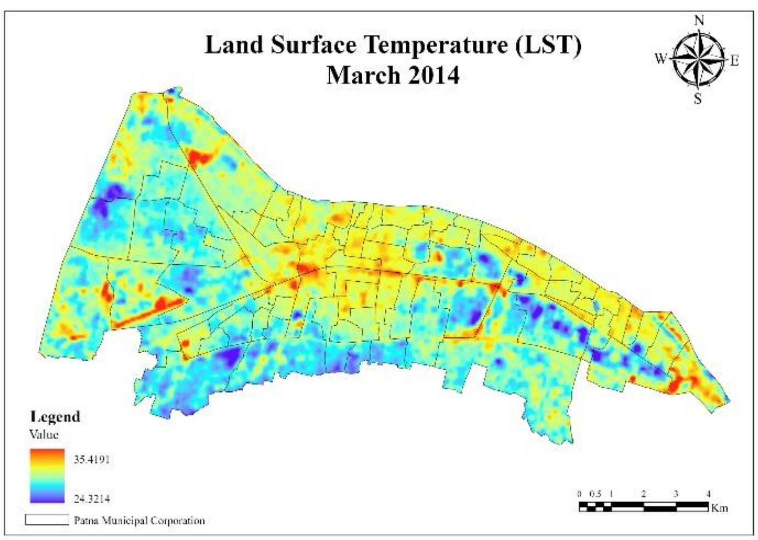
Land surface temperature (LST) is the temperature felt while touching the land surface with one's hands or the ground's skin temperature[23]. LST mapping aims to demonstrate a flexible and straightforward conceptual framework relying upon satellite thermal data that shows surface

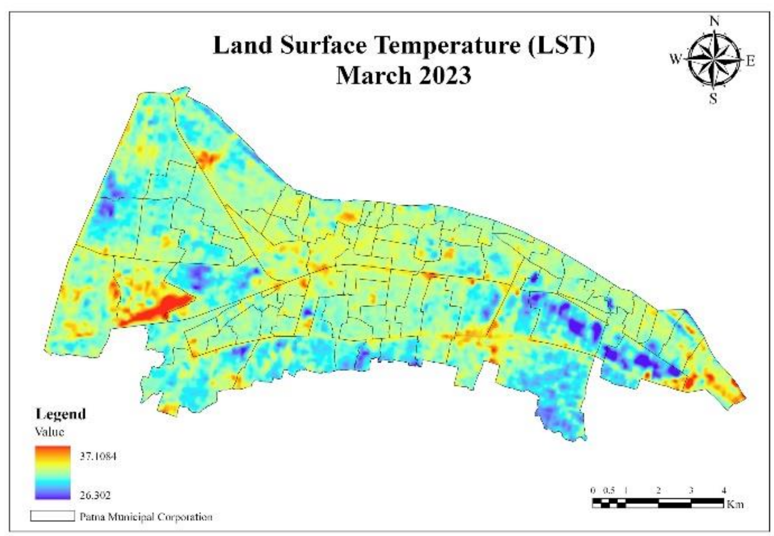
[23] Rajeshwari, A., & Mani, N. . (2014). Estimation of Land Surface Temperature of Dindigul District Using Landsat 8 Data. International Journal of Research in Engineering and Technology, 03(05), 122–126. https://doi.org/10.15623/ijret.2014.0305025

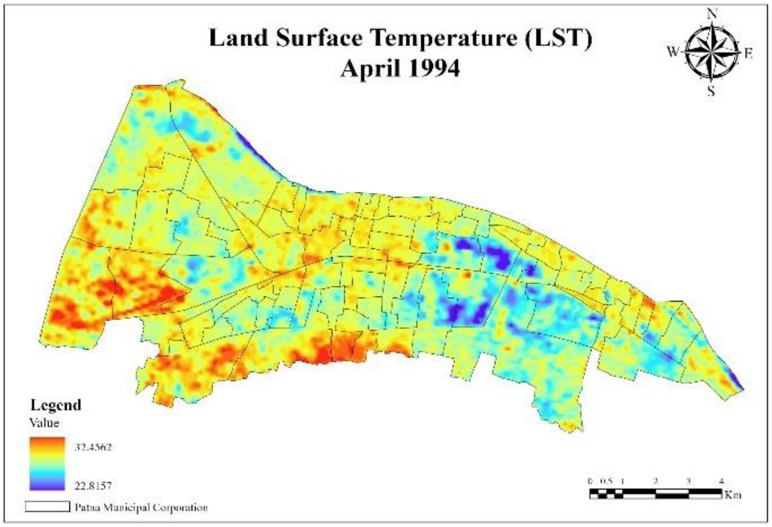
temperature trends and variability and areas at high risk (i.e. areas with high temperature compared to surrounding) in Patna City. The data used to determine LST and surface emissivity are Landsat satellite images from 1990 to 2023 for the pre-monsoon months., which are downloaded from the official website of the US Geological Survey (USGS). The study area is located in the Landsat path/row of 141/42.

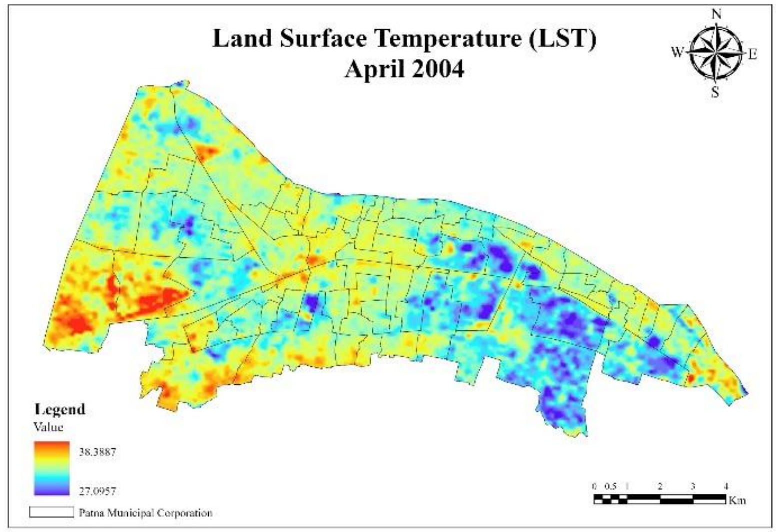


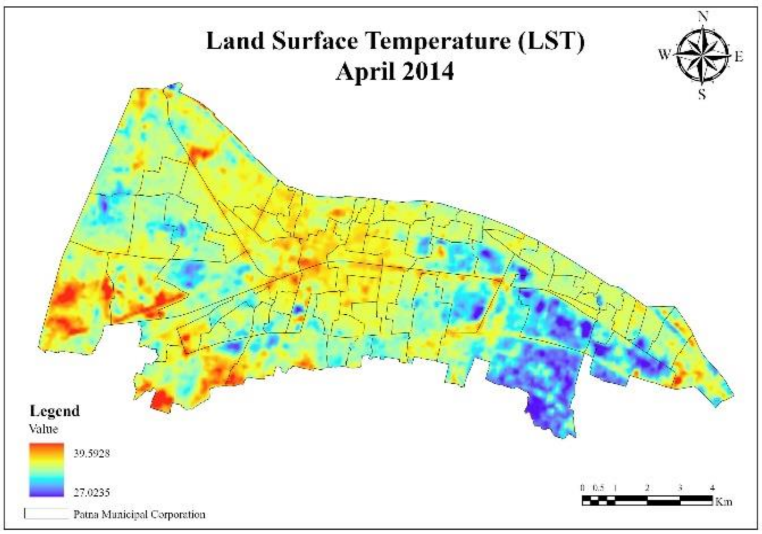


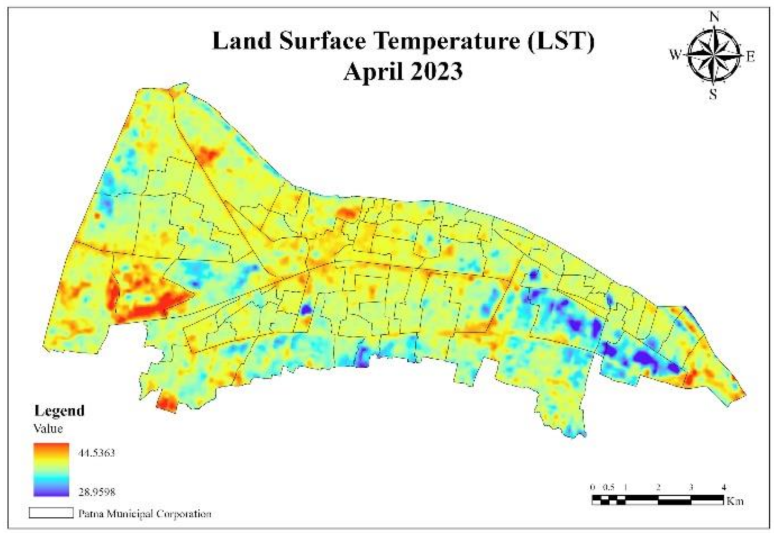


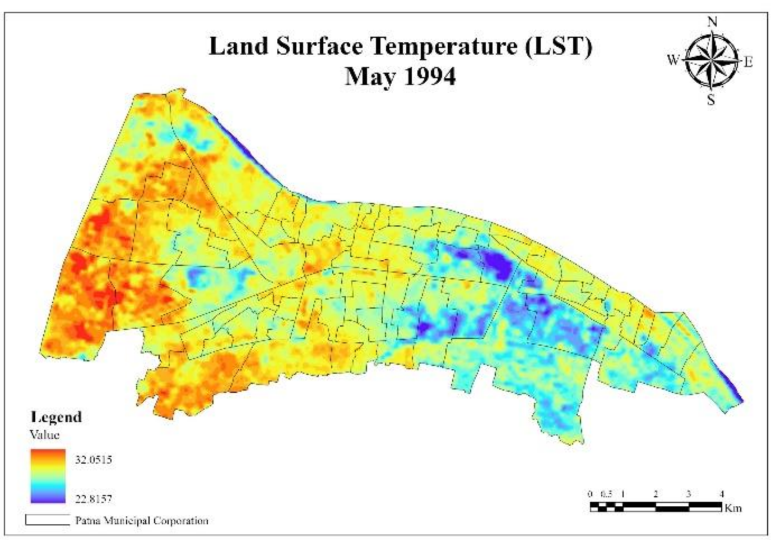


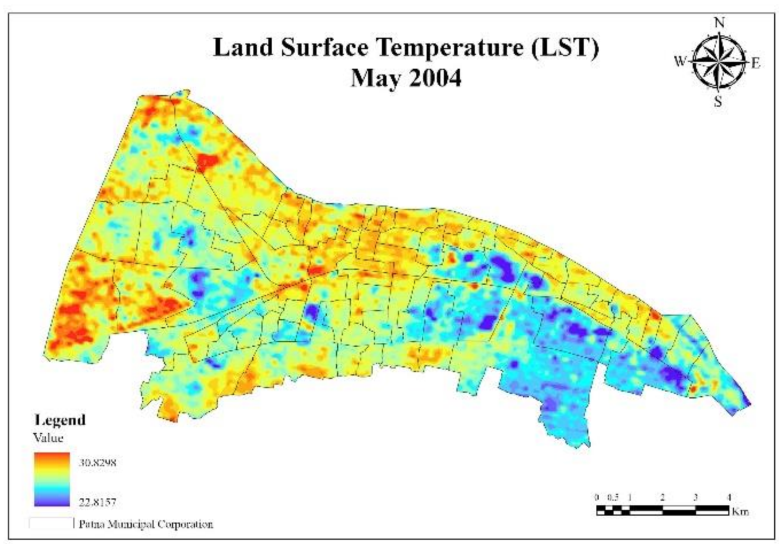

Land Surface Temperature (LST)
April 1994
N
W
E
S
Legend
Value
32.4562
22.8157
Patna Municipal Corporation
0 0.5 1 2 3 4
Km


Land Surface Temperature (LST)
April 2004
N
W
E
S
Legend
Value
38.3887
27.0957
Patna Municipal Corporation
0 0.5 1 2 3 4
Km


Land Surface Temperature (LST)
April 2014
N
W
E
S
Legend
Value
39.5928
27.0235
Patna Municipal Corporation
0 0.5 1 2 3 4
Km


Land Surface Temperature (LST)
April 2023
N
W
E
S
Legend
Value
44.5363
28.9598
Patna Municipal Corporation
0 0.5 1 2 3 4
Km


Land Surface Temperature (LST)
May 1994
N
W
E
S
Legend
Value
32.0515
22.8157
Patna Municipal Corporation
0 0.5 1 2 3 4
Km


Land Surface Temperature (LST)
May 2004
N
W
E
S
Legend
Value
30.8298
22.8157
Patna Municipal Corporation
0 0.5 1 2 3 4
Km

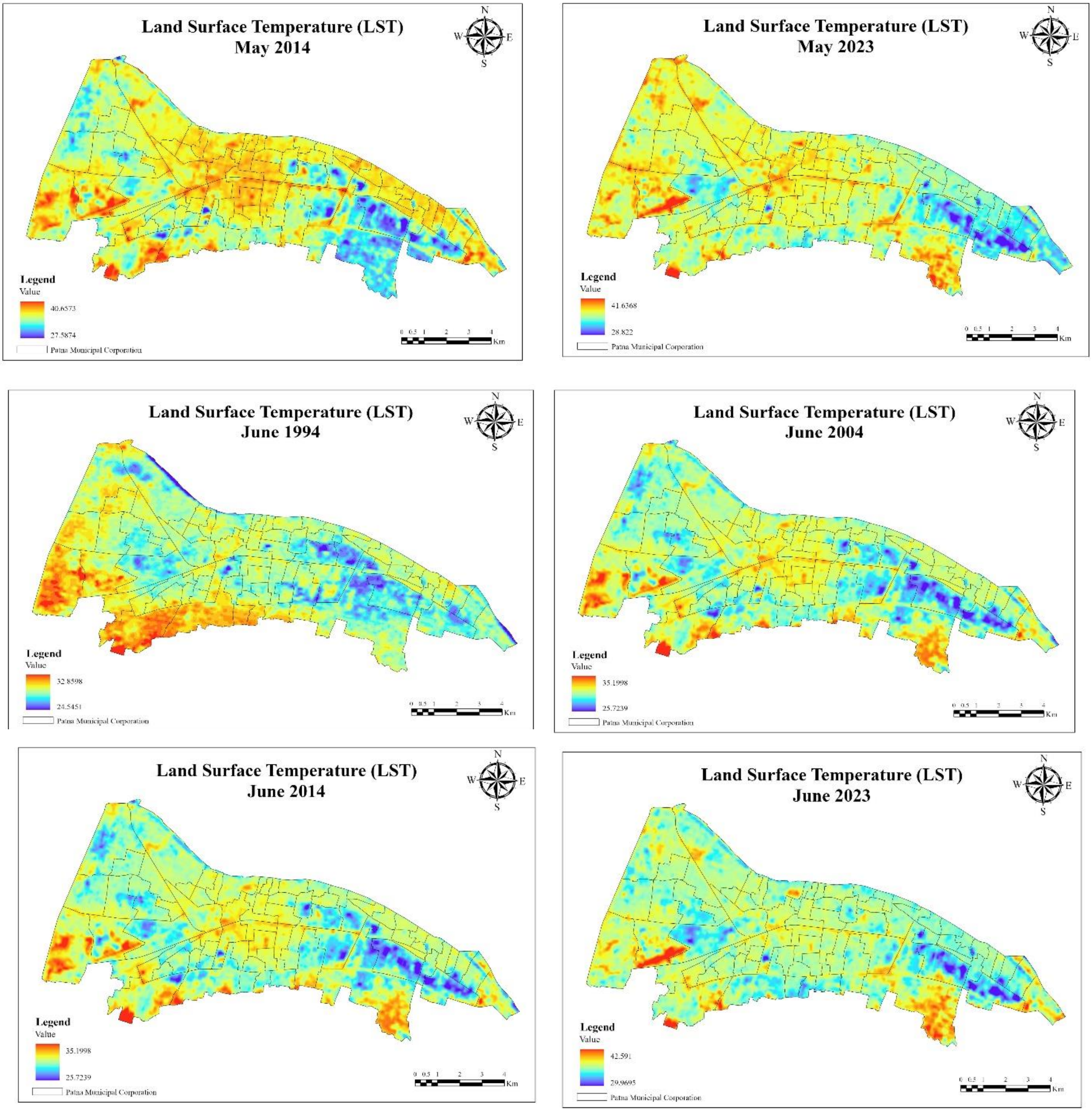


Figure 12- Land Surface Temperature

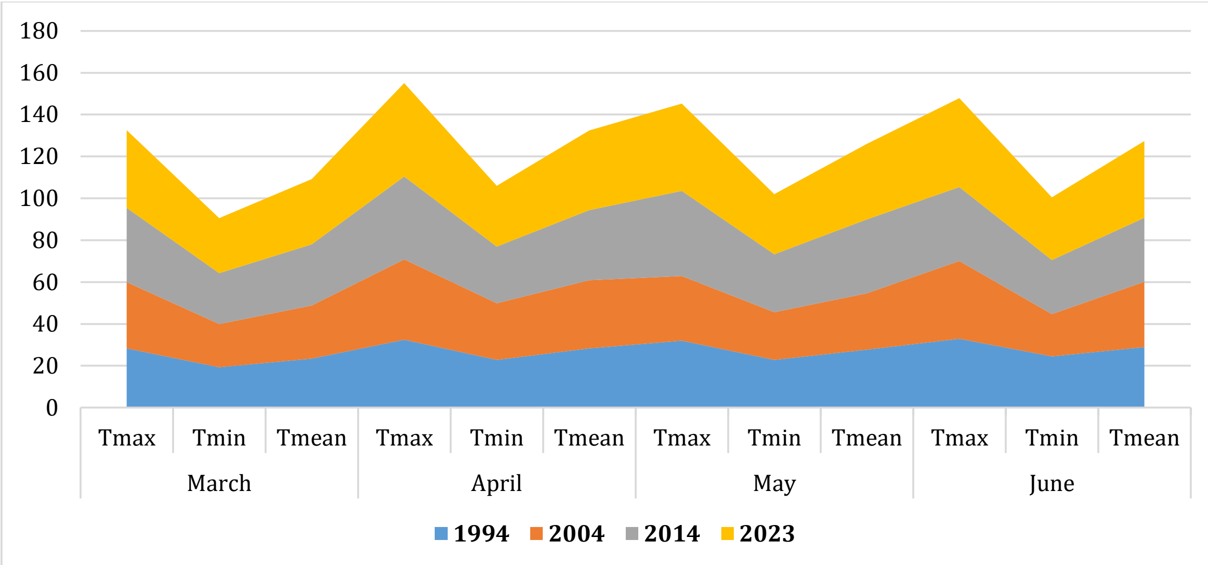


Figure 13 - Pre-Monsoon Land Surface Temperature Trends (1994-2023)

Table 2- Land Surface Temperature (Tmax, Tmin, and Tmean) from 1994 to 2023 (March to June)

Year	March			April			May			June		
	Tmax	Tmin	Tmean	Tmax	Tmin	Tmean	Tmax	Tmin	Tmean	Tmax	Tmin	Tmean
1994	28.35	19.28	23.48	32.46	22.82	28.30	32.05	22.82	27.71	32.86	24.55	28.97
2004	31.65	20.62	25.32	38.39	27.10	32.59	30.83	22.82	26.90	37.22	20.18	31.13
2014	35.42	24.32	29.19	39.59	27.02	33.48	40.66	27.59	35.37	35.20	25.72	30.53
2023	37.11	26.30	31.11	44.54	28.96	38.06	41.64	28.82	36.09	42.59	29.97	36.77

Figure- 13 shows that from 1994 to 2023, there has been a significant upward trend in land surface temperatures across Patna Municipal Corporation, particularly between March and June. The maximum and minimum temperatures have steadily risen, with March's Tmax increasing from 28.35°C in 1994 to 37.11°C in 2023, and Tmin rising from 19.28°C to 26.30°C. April showed the most dramatic rise, with Tmax surging from 32.46°C to 44.54°C over the same period, and Tmin increasing from 22.82°C to 28.96°C. This reflects an alarming rise in pre-summer heat. May and June also experienced substantial increases in Tmax and Tmin, with June's Tmax rising by nearly 10°C, from 32.86°C to 42.59°C. The average temperatures (Tmean) in these months indicate progressively hotter seasons, with the most pronounced warming seen in April. The data highlights a steady increase in both maximum and minimum temperatures across all months, pointing to a significant warming trend in the region.This overall rise in temperatures highlights the growing impact of climate change, particularly in terms of increased heat stress, which has implications for public health and urban planning in the region

The LST analysis of the last 30 years (i.e. 1990-2023) shows that wards Ward 3, 72, 4 amd 22 embrace the most heat hotspots with higher temperatures than other city wards. The presence of a large airport, major busy highway (blacktopped road surface) and limited to no vegetation and water bodies, can be considered significant factors for maximum temperatures in these areas. The maximum and minimum land surface temperatures have been extracted for each ward using a clipped raster by a mask layer, which uses a raster extraction tool in QGIS. The maximum temperature for each ward for April 2023 is presented in Figure 14.

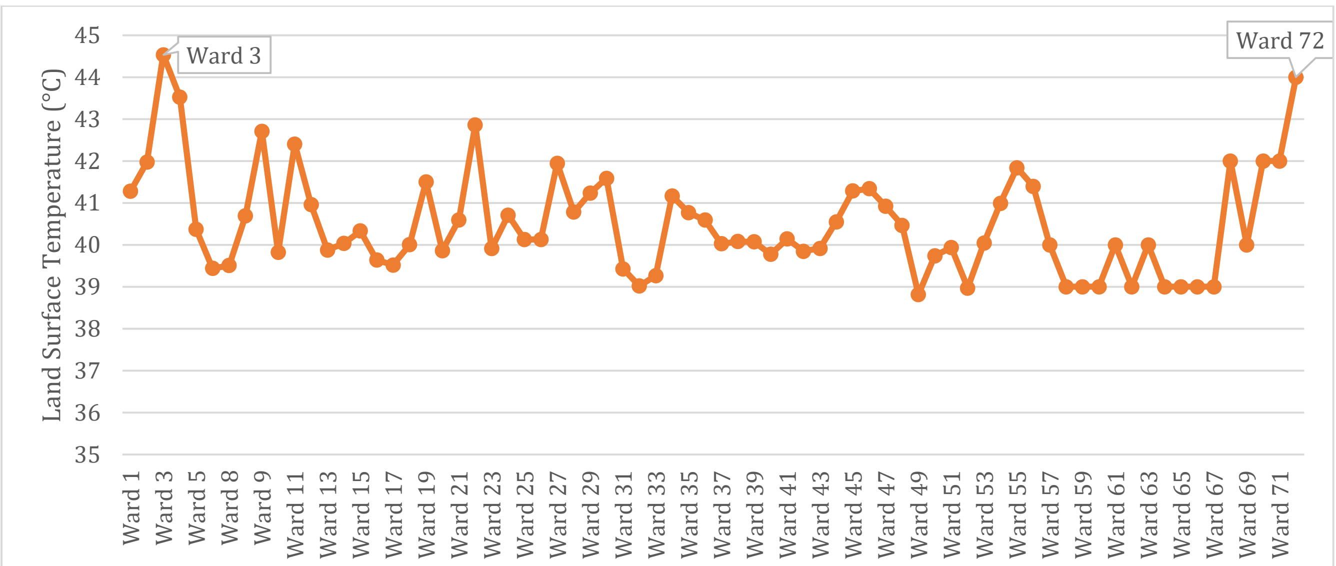


Figure 14- Hotspot ward of Patna Municipal Corporation- Maximum Land Surface Temperature

3.2 Normalised Difference Water Index (NDWI) and Normalised Difference Vegetation Index (NDVI)

To analyse the relationship between landcover changes and urban heat island effect (UHI), a quantitative method in studying the relationship between temperature and the NDVI and NDWI has also been investigated. Data for the year 2023 has been analysed for NDVI and NDWI investigations to get an overall understanding of the latest situation.

The high NDWI value is observed in ward 70, 56 and 71, which indicates they have more water and vegetation surface content compared to other wards, while the lowest NDWI is found in ward 14, indicating the built-up area and bare land are more in this ward. Unlike other wards, there are no water surfaces. The NDWI study confirms that this is because of the high vegetation water content in the city's western side.

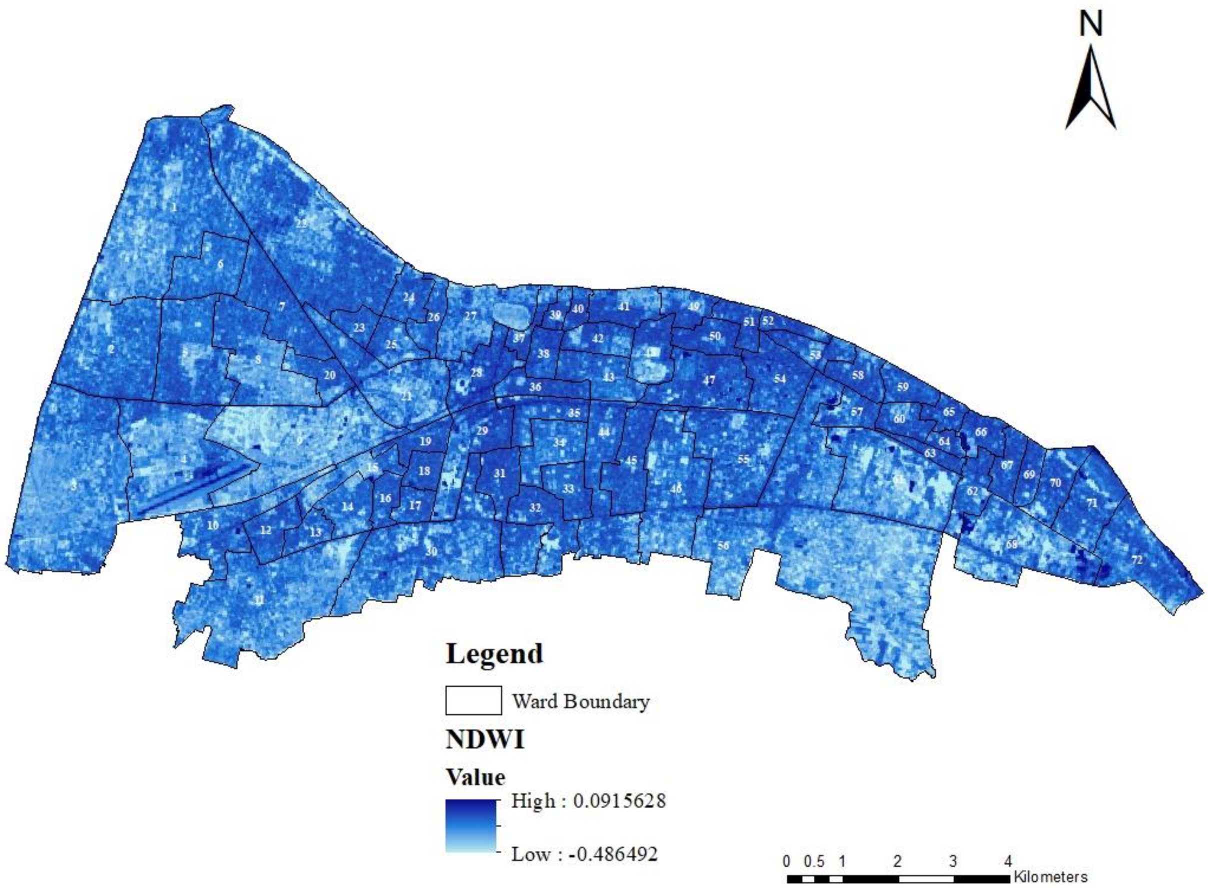


Figure 15- Normalised Difference Water Index (NDWI) for Patna Municipal Corporation

The NDVI is a measure of surface reflectance which gives a quantitative estimation of vegetation growth and biomass. Here, low values of NDVI (0.1 and less) correspond to vegetation free regions and stony and sandy areas. Moderate index values (0.2–0.5) show sparse vegetation such as shrubs and grasslands or senescing crops. Ward 9 and 56 of PMC has the highest NDVI. However, as seen in Figure 13, PMC has very little healthy vegetation. This might be another reason for the temperature increase in the city. As we know, trees and vegetation have lower surface and air temperatures resulting from the shade they provide and through evapotranspiration[24]. Summer peak temperatures can be reduced by 1–5°C when evapotranspiration is used alone or in combination with shading[25].

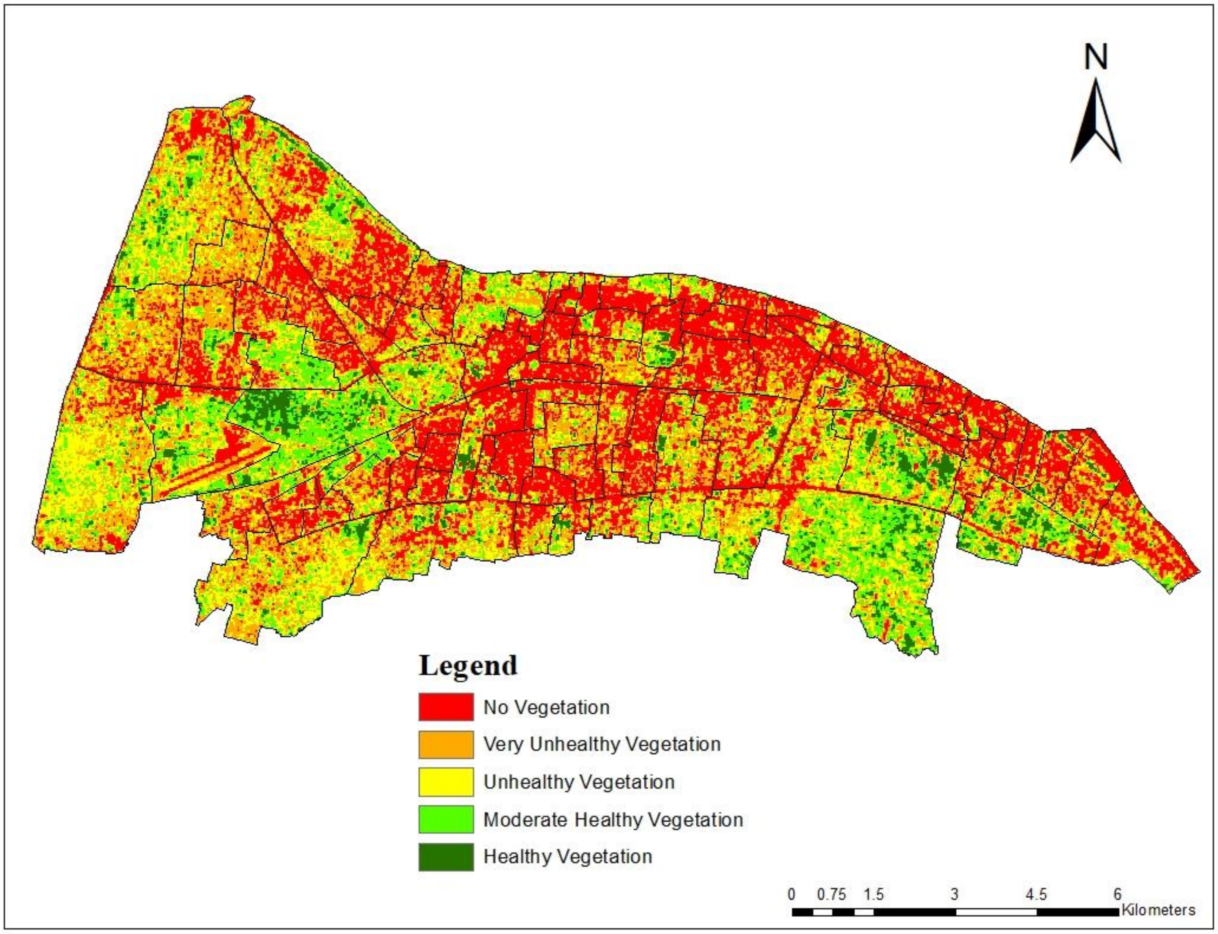


Figure 16- Normalised Difference Vegetation Index (NDVI) for Patna Municipal Corporation

3.3 Land Use and Land Cover (LULC)

From the analysis of different Landsat imageries, the land use cover classification is performed. The classification was based on the five classes; they are (1) Agriculture Land, (2) Barren Land, (3) Built-up area, (4) Vegetation, (5) Water Body. The LULC images are shown in Figure. 17., and the analytical data is provided in Table 3. The land change matrix is shown in Table 4.

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[24] Akbari, H., M.Kurn, D., E.Bretz, S., & W.Hanford, J. (1997). Peak power and cooling energy savings of shade trees. *Energy and Buildings*, 25(2), 139–148. https://doi.org/10.1016/S0378-7788(96)01003-1

[25] Huang, Y. J., Akbari, H., & Taha, H. (1990). The wind-shielding and shading effects of trees on residential heating and cooling requirements. *Proceedings of the ASHRAE Winter Conference*, 1403–1411.

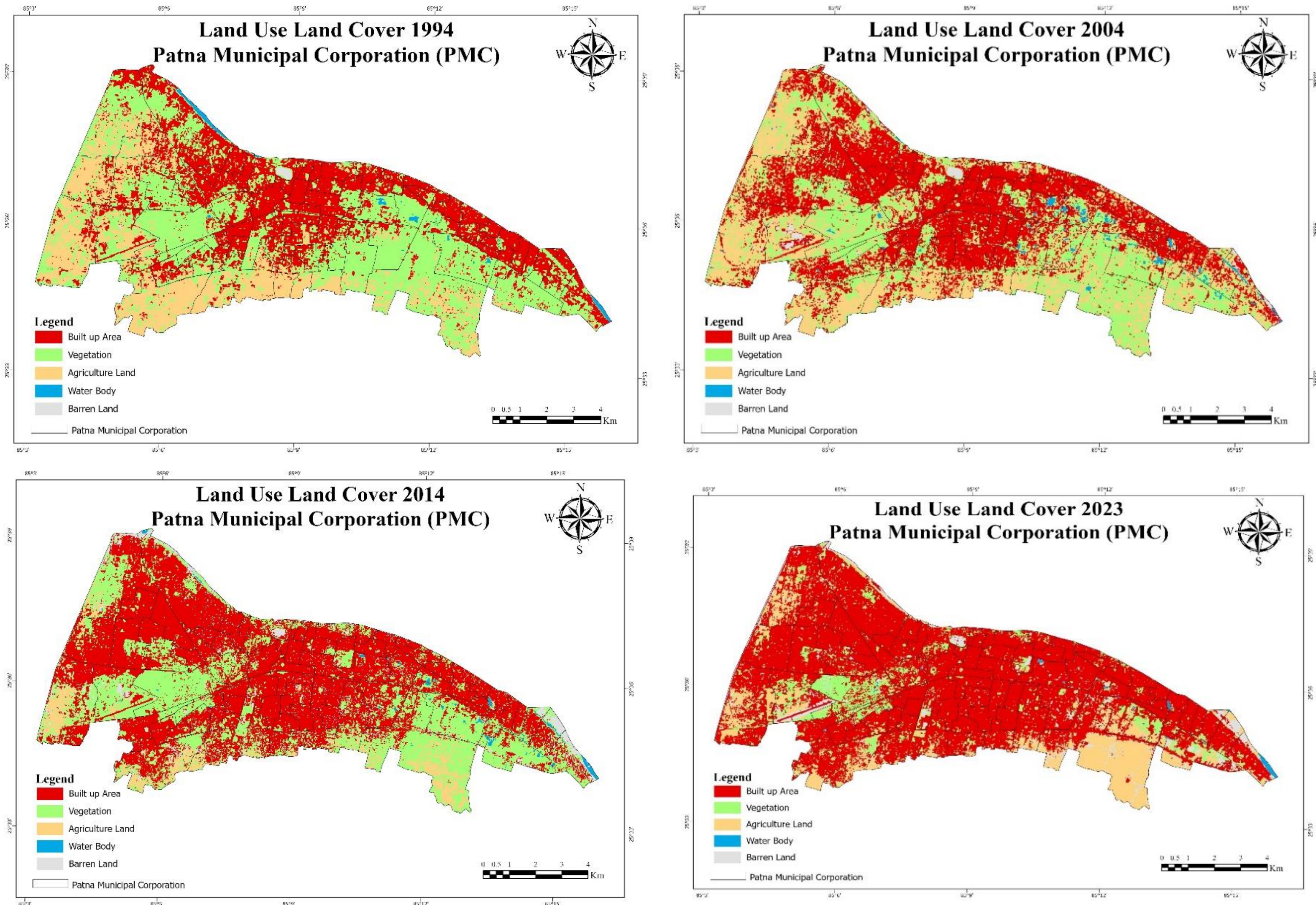

Figure 17- Land Use Land Cover for Patna Municipal Corporation for four decades

Table 3- LULC of PMC

Land use land cover Classes	1994		2004		2014		2023		Change from 1994-2023	
	Km^2	%	Km^2	%	Km^2	%	Km^2	%	Km^2	%
Agriculture Land	24.09	22.75%	27.32	25.80%	14.09	13.31%	12.46	11.77%	-11.63	-10.99%
Barren Land	0.26	0.24%	1.04	0.98%	4.43	4.18%	5.05	4.77%	4.79	4.52%
Built up Area	34.76	32.83%	43.67	41.24%	59.08	55.80%	77.27	72.95%	42.51	40.12%
Vegetation	46.13	43.57%	32.78	30.95%	27.69	26.15%	10.79	10.19%	-35.34	-33.38%
Water Body	0.64	0.60%	1.08	1.02%	0.59	0.56%	0.35	0.33%	-0.29	-0.27%

Table 4- Land Change Matrix (1994 – 2023)

Land Use Land Cover		2023				
		Agriculture Land	Barren Land	Built-Up Area	Vegetation	Water Body
1994	Agriculture Land	6.839	1.006	14.773	1.430	0.004
	Barren Land	0.029	0.178	0.048	0.003	0.000
	Built Up Area	0.997	0.811	32.131	0.768	0.033
	Vegetation	8.396	2.875	28.055	6.558	0.175
	Water Body	0.147	0.140	0.178	0.028	0.134

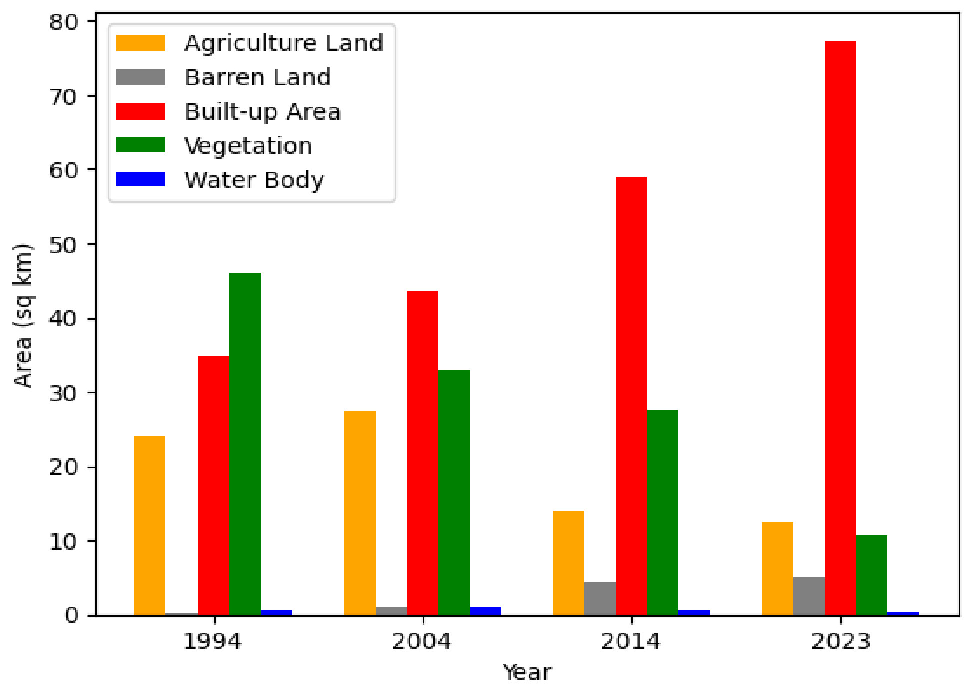

Figure 18- Land use changes over time

Table- 3 reveals that in 1994, the area covered under Agriculture Land was about 22.75% (24.09 km^2), Barren Land covered 0.24% (0.26 km^2), the Built-Up Area comprised 32.83% (34.76 km^2), Vegetation covered 43.57% (46.13 km^2), and Water Bodies accounted for 0.60% (0.64 km^2). By 2023, significant changes were observed: Agriculture Land reduced to 11.77% (12.46 km^2), Barren Land increased to 4.77% (5.05 km^2), the Built-Up Area expanded to 72.95% (77.27 km^2), Vegetation dramatically decreased to 10.19% (10.79 km^2), and Water Bodies slightly decreased to 0.33% (0.35 km^2).

The most significant shifts occurred between Built-Up Area and Vegetation, where the Built-Up Area increased by 40.12% (42.51 km^2) over the study period, while Vegetation decreased by 33.38% (35.34 km^2). Agriculture Land also saw a notable decline of 10.99% (11.63 km^2), suggesting conversion to urban uses or degradation into Barren Land, which saw a 4.52% (4.79 km^2) increase. Water Bodies experienced a small decrease of 0.27% (0.29 km^2).

The results indicate rapid urbanization as the main driver of land-use changes, with natural landscapes, particularly vegetation and agricultural areas, being replaced by built-up areas. This trend highlights the potential environmental consequences of urban growth, such as loss of biodiversity and reduced agricultural productivity.

The table 4 matrix reveals significant land-use transformations, particularly the conversion of natural and agricultural areas into urbanized zones. From 1994 to 2023, about 14.77 km^2 of Agriculture Land was converted into Built-Up Area, along with 28.06 km^2 of Vegetation. Additionally, 1.43 km^2 of Agriculture Land and 2.88 km^2 of Vegetation transitioned into Barren Land, indicating degradation or abandonment of these lands. A smaller portion of 0.18 km^2 of Water Body was converted into Built-Up Area, further reflecting urban expansion at the expense of natural ecosystems.

Built-Up Area saw the most dramatic increase, gaining 42.51 km^2 over the study period, primarily at the expense of Agriculture Land and Vegetation. This expansion highlights the rapid urbanization in the region and its impact on natural resources.

The decline in Vegetation and Agriculture Land indicates potential environmental degradation, biodiversity loss, and reduced agricultural productivity, while the modest shift in Water Bodies to Built-Up Area underscores the increasing pressure on water resources due to urban growth. The matrix serves as an essential tool for understanding land-use changes, highlighting the need for sustainable urban planning to mitigate adverse environmental impacts.

3.4 Change in Built Up Area (1990-2023)

Figure-19 shows that from 1990 to 2023, the dynamics of land use changes between built-up and non-built-up areas have shown notable trends. The conversion rate from Built-Up Area to Non-Built-Up Area stands at 8.12%, indicating that established urban areas are relatively stable and less prone to reverting to natural or agricultural land. In contrast, the conversion from Non-Built-Up Area to Built-Up Area is significantly higher at 55.34%, demonstrating a strong trend of urbanization, where natural landscapes and agricultural lands are increasingly being transformed into urban environments.

Additionally, the percentage of Unchanged Built-Up Area is reported at 41.30%, suggesting that a substantial portion of the existing urban landscape has remained intact over this period. These figures reflect the ongoing pressures of urban expansion, which can lead to increased challenges related to environmental sustainability and resource management. The data highlights the need for effective urban planning strategies to accommodate growth while preserving valuable non-built-up areas and ensuring ecological balance.

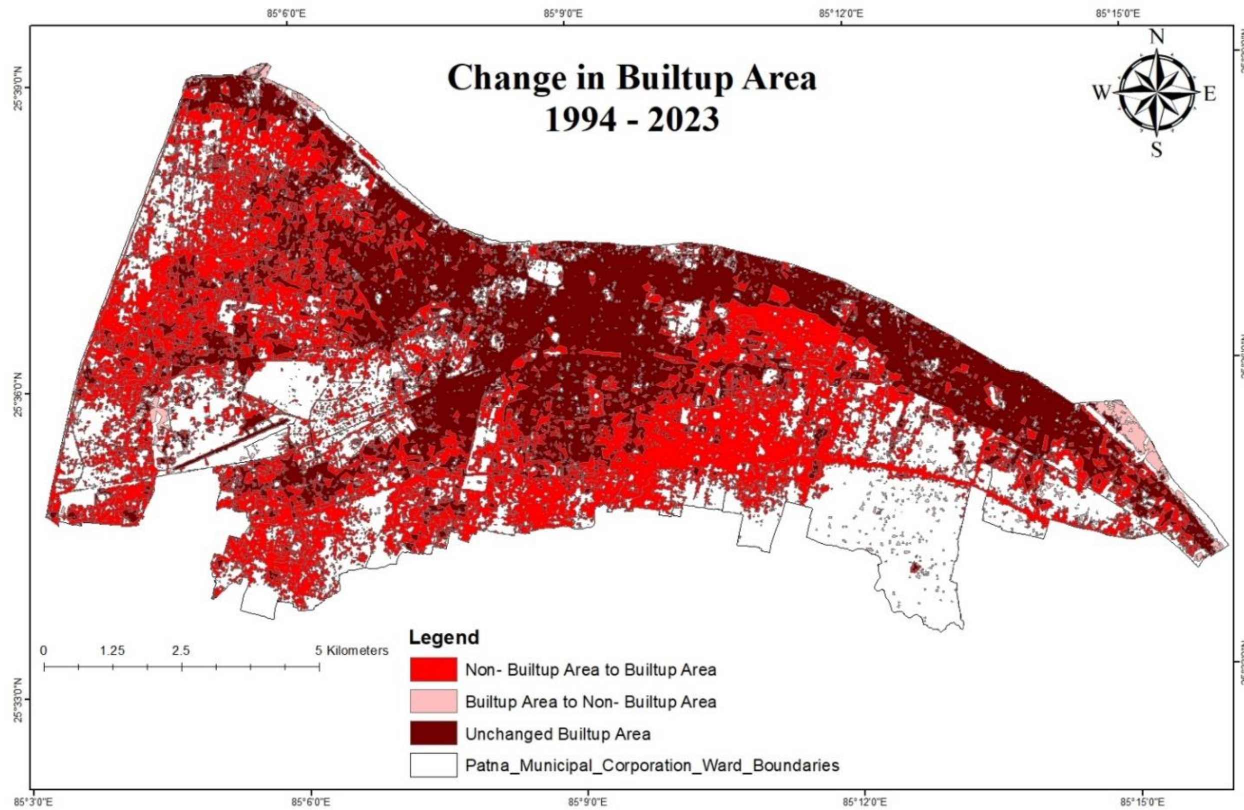

Figure 19- Change in Builtup Area (1994-2023)

3.5 Mean LST for LULC classes

Between 1994 and 2023, a comparison as shown in Table- 5 across different Land Use Land Cover (LULC) classes in Patna reveals distinct warming patterns, with barren land and built-up areas showing the highest temperature increases, followed closely by agricultural land, while vegetation and water bodies also experienced substantial warming, albeit starting from cooler baselines.

In March, barren land consistently exhibited the highest temperatures, rising from 25.01°C in 1994 to 31.33°C in 2023. Built-up areas followed a similar trajectory, with temperatures increasing from 23.91°C to 31.26°C. Agricultural land, while also warming, remained slightly cooler than built-up areas, rising from 23.66°C to 30.94°C. Vegetation and water bodies, traditionally cooler LULC classes, saw notable increases, with vegetation rising from 23.09°C to 30.68°C, and water bodies from

20.51°C to 30.48°C. This indicates that even the natural cooling effect of vegetation and water has diminished significantly.

Table 5- Mean LST in degree Celsius ((°C) of Study Area for pre-monsoon

March				
LULC Classes	**1994**	**2004**	**2014**	**2023**
Agriculture Land	23.66	25.43	28.77	30.94
Barren Land	25.01	27.48	29.55	31.33
Built up Area	23.91	25.51	29.47	31.26
Vegetation	23.09	24.88	28.69	30.68
Water Body	20.51	23.73	27.47	30.48
April				
LULC Classes	**1994**	**2004**	**2014**	**2023**
Agriculture Land	28.65	32.89	33.59	37.59
Barren Land	29.09	33.99	34.10	38.27
Built up Area	29.05	32.97	33.90	38.01
Vegetation	27.67	31.69	32.70	37.22
Water Body	25.36	30.29	30.74	36.46
May				
LULC Classes	**1994**	**2004**	**2014**	**2023**
Agriculture Land	37.59	27.03	35.47	35.96
Barren Land	38.27	27.56	35.93	36.22
Built up Area	38.01	27.27	35.85	36.21
Vegetation	37.22	26.19	34.48	34.98
Water Body	36.46	25.03	32.07	33.66
June				
LULC Classes	**1994**	**2004**	**2014**	**2023**
Agriculture Land	28.56	31.06	30.69	36.79
Barren Land	29.92	31.62	31.86	37.24
Built up Area	29.03	31.36	30.81	37.04
Vegetation	28.48	30.28	30.01	35.67
Water Body	25.85	28.05	28.20	35.57

In April, barren land and built-up areas displayed the most pronounced warming, with barren land increasing from 29.09°C in 1994 to 38.27°C in 2023, and built-up areas following closely, rising from 29.05°C to 38.01°C. Agricultural land and vegetation also warmed substantially, reaching 37.59°C and 37.22°C, respectively. Water bodies, although cooler overall, showed a significant increase from 25.36°C to 36.46°C, further highlighting the extent of temperature rises even in natural cooling zones. By May, all LULC classes experienced high temperatures, but barren land (36.22°C) and built-up areas (36.21°C) remained the hottest, reflecting the persistent heat accumulation in urbanized and barren regions. Agriculture land, vegetation, and water bodies showed slightly lower, yet still significant, increases, reaching 35.96°C, 34.98°C, and 33.66°C, respectively.

In June, barren land continued to be the hottest, rising from 29.92°C to 37.24°C, followed closely by built-up areas at 37.04°C. Agricultural land also showed a considerable increase, from 28.56°C to 36.79°C. Vegetation and water bodies, which typically help moderate temperatures, showed alarming increases, with vegetation rising from 28.48°C to 35.67°C, and water bodies from 25.85°C to 35.57°C.

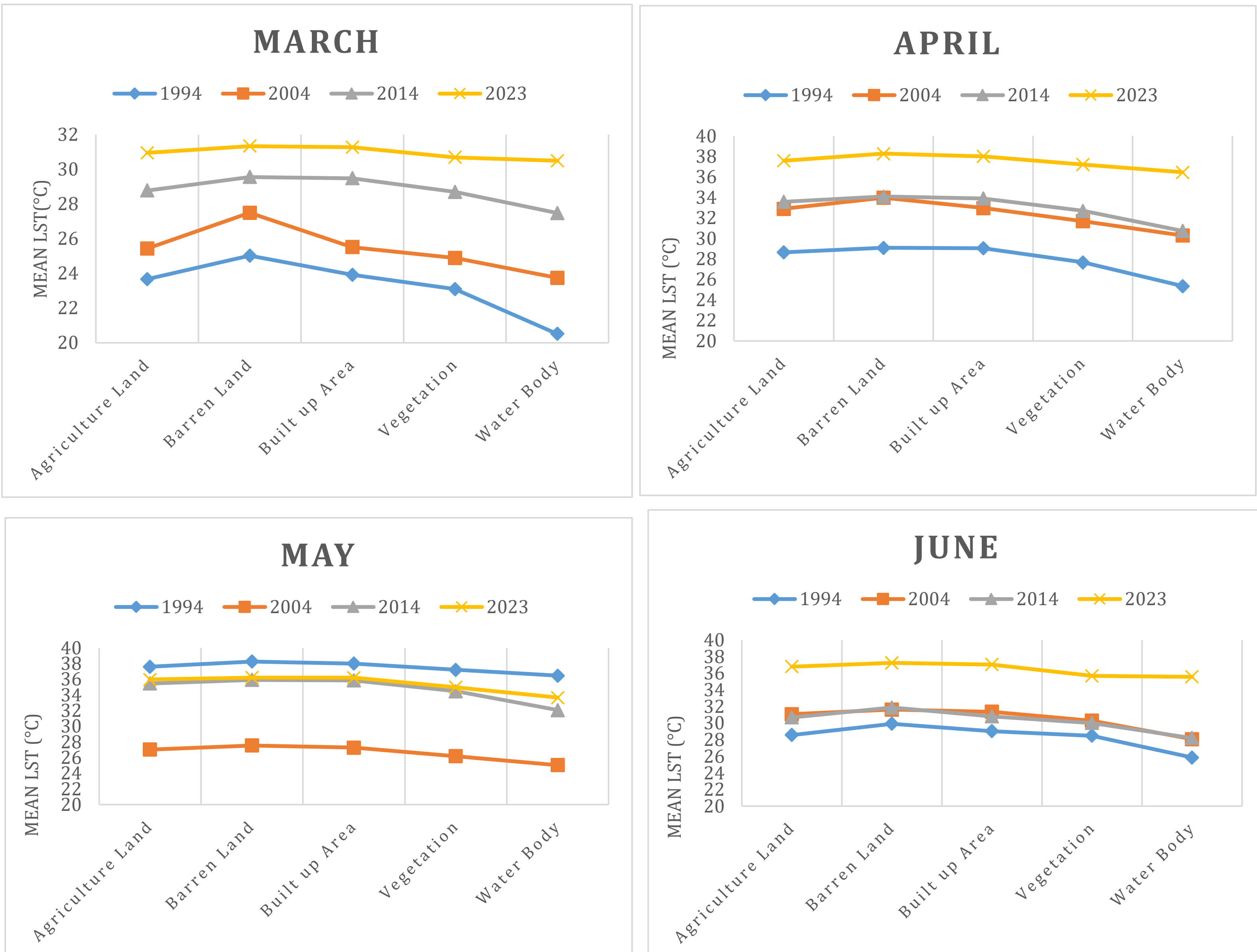

Figure 20- LST Trend across different LULC classes

Overall, barren land and built-up areas consistently recorded the highest temperatures across all months, indicating the amplifying effects of urbanization and loss of vegetation. While natural land cover such as vegetation and water bodies started with lower baseline temperatures, their significant warming over the years suggests a diminishing ability to mitigate heat. This comparison underscores the increasing vulnerability of Patna's land cover to rising temperatures, driven by both human-induced changes and climate change impacts.

4 Mapping of Heat Hotspots

The thermal hot-spot maps give insight into the differences in hot spot distribution within cities. Identifying hot spots within a city can help focus interventions where they are most needed during heat waves.

> **'Hot-spots' are considered as the areas within the city which experience ambient temperature in excess of the average monthly maximum temperature.**

Such thermal maps provide information about the areas which have the accumulation of hotspots, and therefore population living there is under high physiological and socio-economic risks due to thermal stress. Thus, specific measures to curb the problem of heat stress for the resident population can be taken using these maps. The hotspot maps so generated are useful for policymakers and city administrators in analysing the local factors contributing to heat-stress in different wards and devising mitigation options to reduce heat stress in these areas.

4.1 Delineation of Hotspots

To delineate the hotspots, the percentile method was adopted. In this approach, first the areas experiencing temperature above 95% of highest LST observed on a particular date were extracted. These areas represent the thermal hotspots at temperatures in excess of 95% of highest LST measured on the particular date. Extraction of hotspots based on percentile of highest temperature observed in the LST map. For each LST map, areas experiencing LST more than 95%, 90%, 85% of the highest LST range were extracted.

Category I	•Wards having more than 50% of the area as thermal hotspot
Category II	•Wards having 25-50% of the area as thermal hotspot
Category III	•Wards having 10-25% of the area as thermal hotspot
Category IV	•Wards having less than 10% of the area as thermal hotspot

Figure 21- Hotspot Delineation methodology

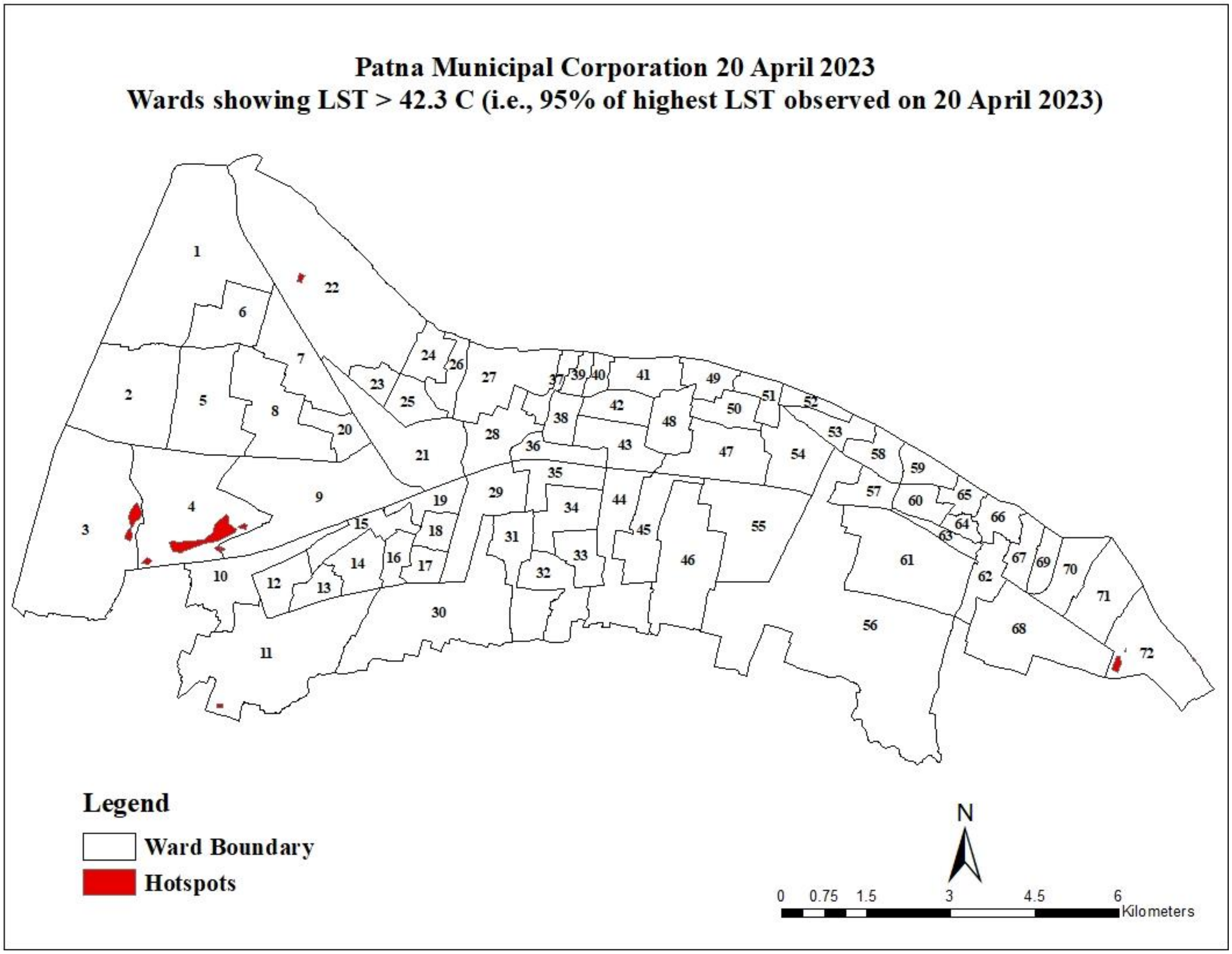

Figure 22- Thermal hotspot map showing wards with LST>95% of highest LST observed in 2023

Ward no- 4 has more than 60% of area followed by Ward no-3 and 72 as thermal hotspot

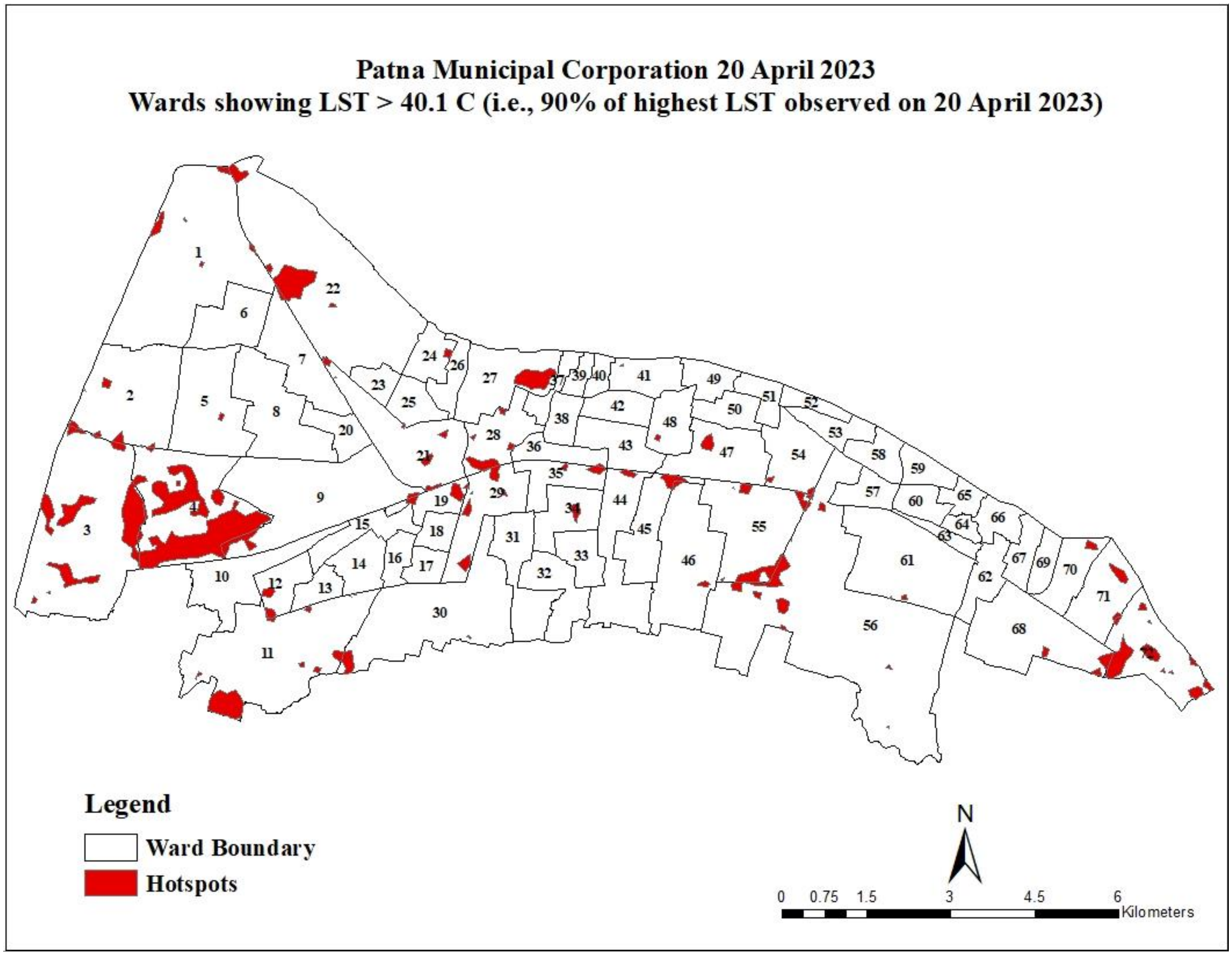

Figure 23- Thermal hotspot map showing wards with LST>90% of highest LST observed in 2023

Ward no-4 and 3 has more than 15% area and Ward no- 22, 72 and 11 has more than 5% area as thermal hotspot

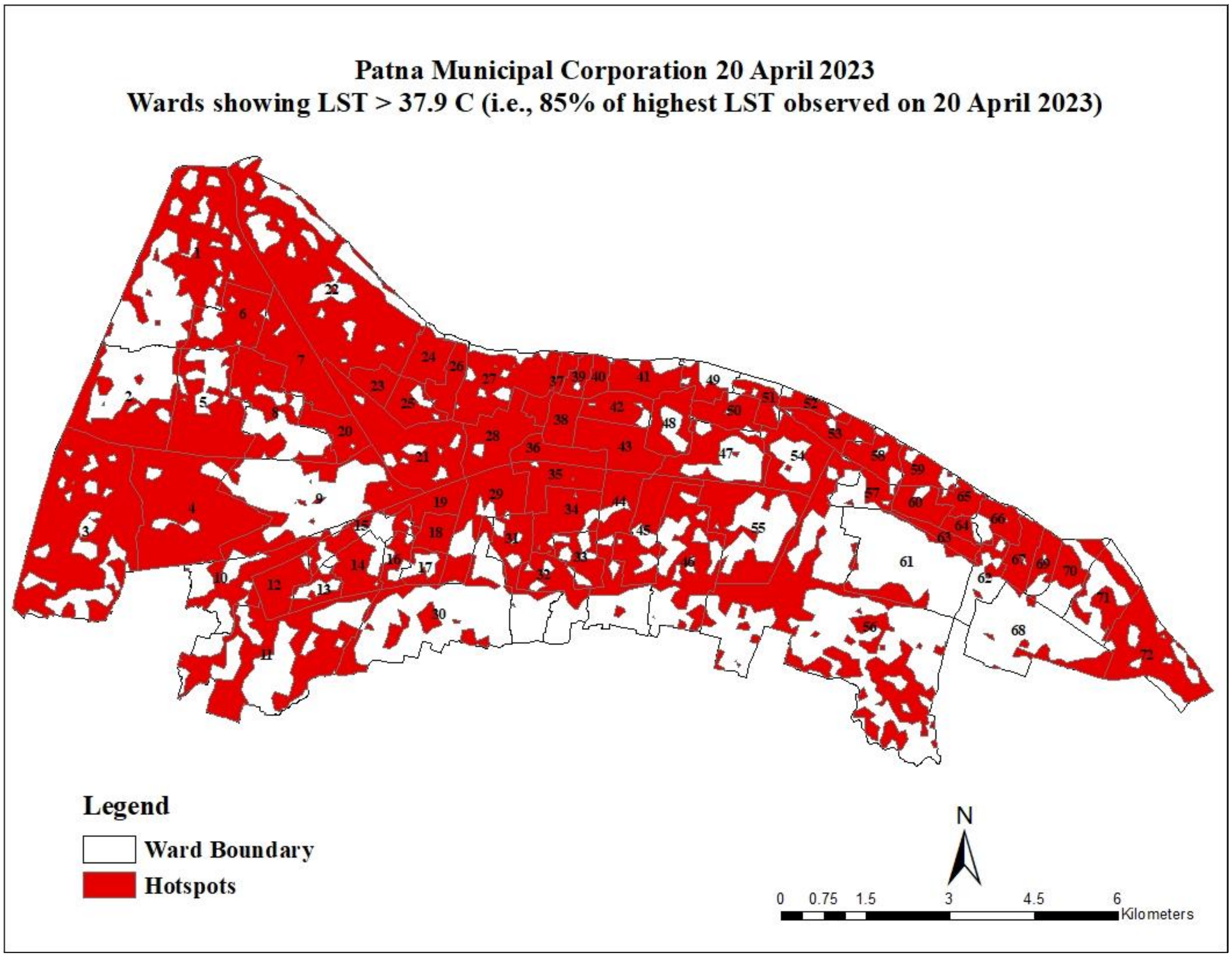

Figure 24- Thermal hotspot map showing wards with LST>85% of highest LST observed in 2023

Almost 64% of the total area as thermal hotspot which has LST> 85%

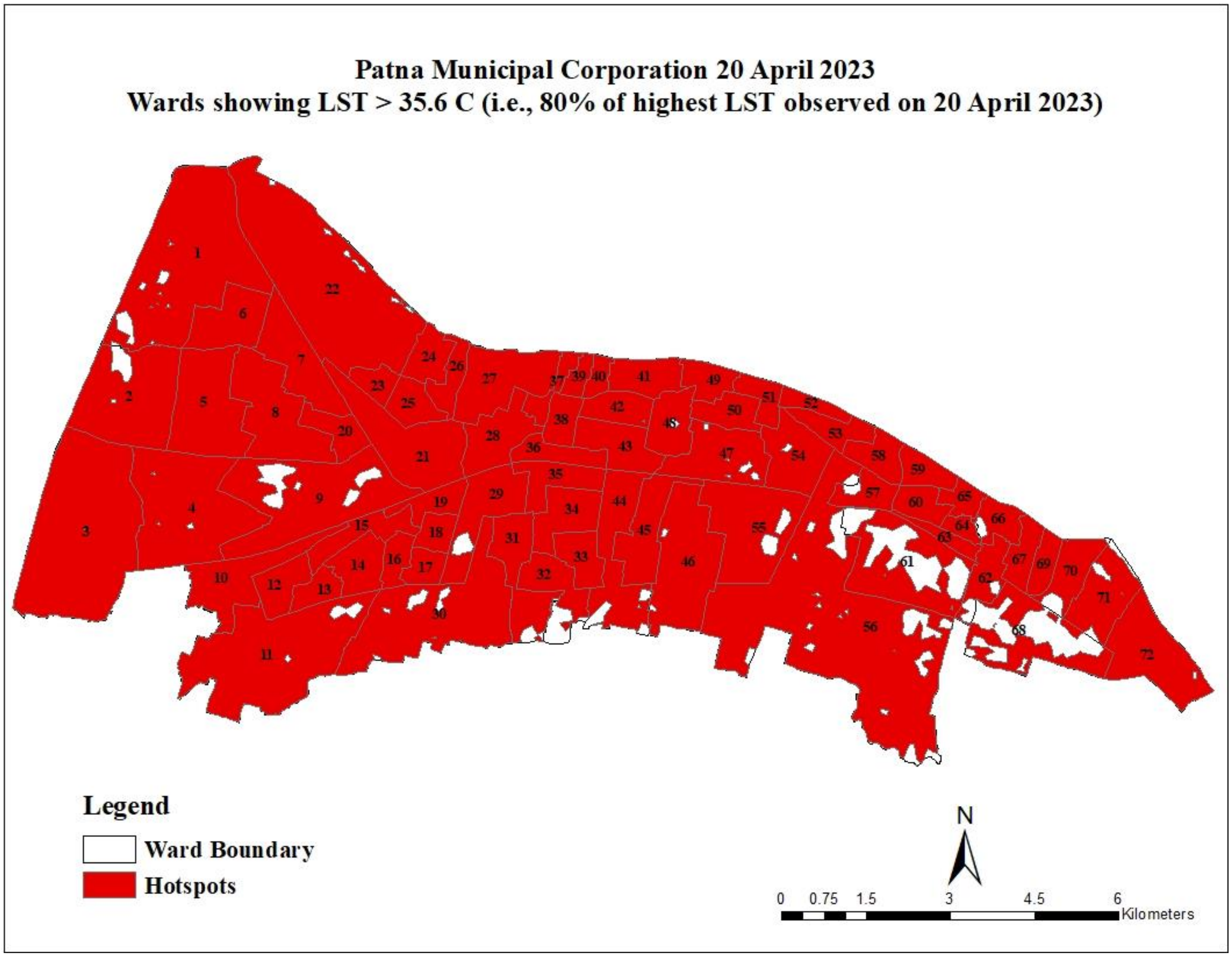

Figure 25- Thermal hotspot map showing wards with LST>80% of highest LST observed in 2023

Almost 84% of the total area as thermal hotspot which has LST> 80%

4.2 Exposure Analysis

An exposure map is critical to understand heatwave risk. Exposure is the location, attributes, and value of assets critical to communities (people, buildings, factories, farmland, etc.) which could be affected by a hazard. Due to the predominance of concrete surfaces in the city, temperatures in built-up areas and densely populated parts, tend to be hotter than those in the surrounding countryside. The table-6 presents a list of indicators along with the rationale behind their inclusion in the assessment.

Table 6- List of indicators, their dimensions, and rationale for the selection

Indicators	Dimension	Rationale for Selection
Population Density	Sensitivity (Positive)	Increased population density, population growth and dispersal increase heat susceptibility
Built-up area	Sensitivity (Positivity)	Increase built-up area surfaces, means of transport and industrial activities are major factors towards increasing temperatures in the city area as compared to other areas.
Land Surface Temperature	Sensitivity (Positive)	This gives information about the area with high temperature

Furthermore, all the parameters are normalised to compute normalised heat index scores. The normalisation process has been explained in Table 5 below:

Table 7- Normalisation of indicators for exposure

Normalisation is based on the indicator's functional relationship with vulnerability.
For positively related indicators, i.e. where vulnerability increases with an increase in the value of the indicator, the following formula has been used. $N_P = ((P - Pmin) / (Pmax - Pmin)) \times 100$ **Where P is the value of the respective indicator;** **Pmax is the maximum value of the indicator;** **Pmin is the minimum value of the indicator.**
For negatively related indicators, i.e. where vulnerability decreases with an increase in the value of the indicator, the following formula has been used: $N_N = ((Pmax - P) / (Pmax - Pmin)) \times 100$ **Where P is the value of the respective indicator;** **Pmax is the maximum value of the indicator;** **Pmin is the minimum value of the indicator.**
The higher value of normalisation refers to the region or ward with maximum vulnerability and the lower value of normalisation corresponds to the ward with minimum vulnerability with respect to a particular indicator.

The exposure analysis has been conducted by using normalised scores of population density, LST, and built-up. The sensitivity for all these indicators is positive, which indicates the higher the normalisation value, the greater the exposure.

The formula for the combined exposure:

E = Wt1 × Population + Wt2 × LST + Wt3 × Built-up

After the normalisation process, the individual parameters have been transformed by scaling so that all the parameters come in a similar range. Each normalised value of population density, heat island, and built-up has been multiplied with equal weights, i.e. 0.33. This individual weighted value was selected on the basis of socio economic context through expert judgments.

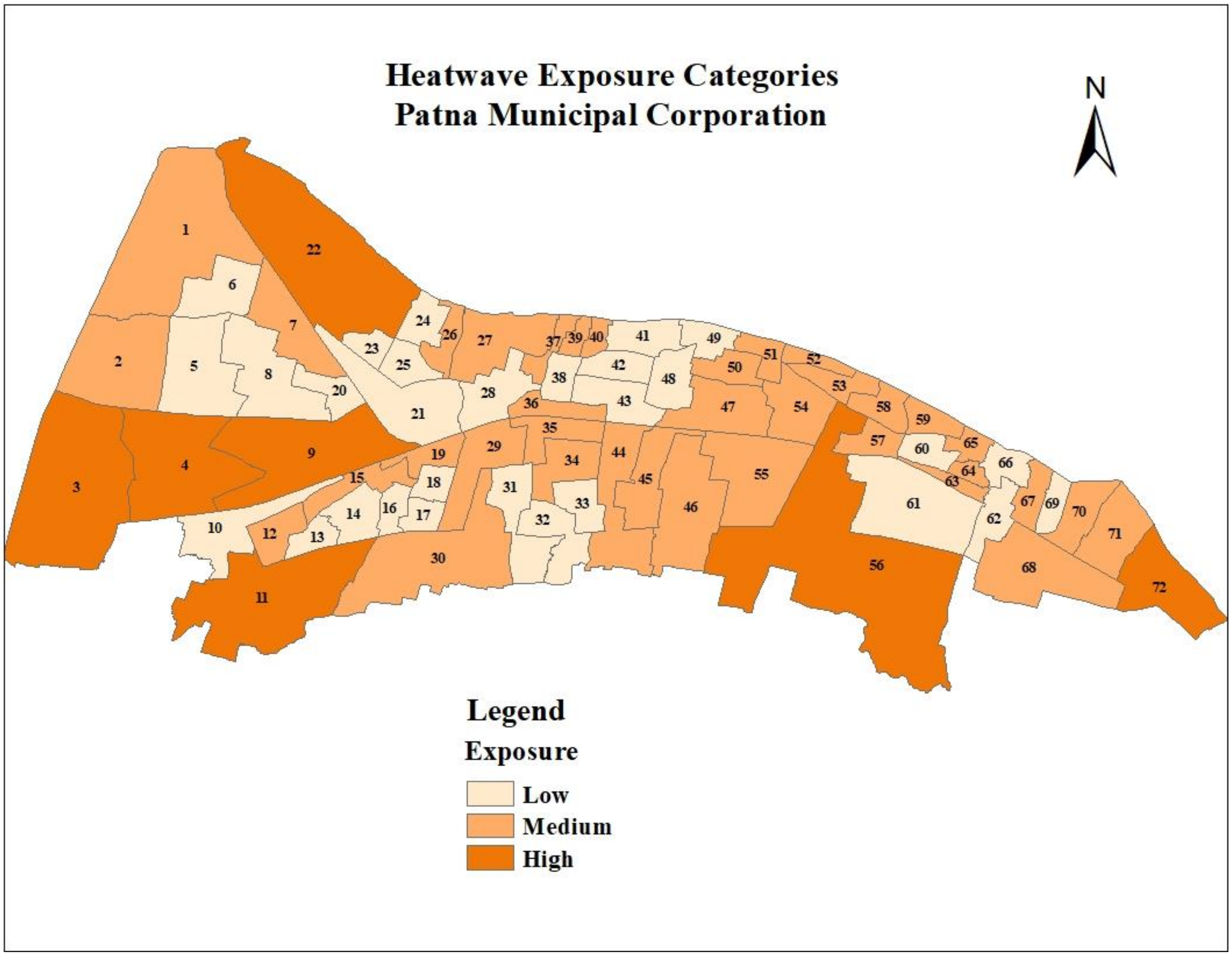

Figure 26- Exposure Analysis of Patna Municipal Corporation

The exposure analysis suggests that several wards, including Ward 3, 56, 22, 11, 9, and 4, are highly exposed and could be significantly affected by heatwave effects. In particular, Ward 3 stands out with the highest exposure level of 48.41, driven by substantial urban growth and expanding built-up areas. Similarly, Wards 56 and 22 also exhibit high exposure levels due to increased land surface temperatures (LST) and population density. Moreover, Wards 30 and 52, both registering exposure levels of 35.74, demonstrate significant vulnerability, exacerbated by their dense populations and the extensive urban landscape. This combination of factors makes these wards particularly susceptible to the adverse impacts of heatwave events.

The data from various wards in Patna Municipal Corporation reveals significant disparities in urban density and built-up infrastructure, impacting the exposure levels across different areas. For instance, Ward No. 22 demonstrates a high population density of 16,287.89, with a built-up length of 70.82 and classified as a high exposure category, indicating a greater vulnerability to urban heat effects. Conversely, Ward No. 9 has a much lower density of 3,065.74 but is categorized as high exposure due to its extensive built-up length of 68.11, reflecting how infrastructure can amplify heat stress despite lower population density.

Several wards, such as No. 19 and No. 26, fall into the medium exposure category with densities of 35,618.03 and 38,296.83 respectively, showcasing balanced built-up lengths and normalized values that suggest a moderate level of vulnerability to heat stress. On the other hand, wards like No. 20 and No. 21 are classified as low exposure areas, despite relatively higher densities (26,755.89 and 10,448.47 respectively), which could indicate better adaptive capacities or lower heat stress effects due to more greenery or water bodies.

The data highlights a complex relationship between built environment characteristics and heat exposure, emphasizing the need for tailored urban planning and heat mitigation strategies that consider local density and built infrastructure to effectively address heat vulnerabilities across Patna's diverse wards.

5 Way Forward

The thermal hotspot analysis and exposure assessment in Patna underscore the urgent need for immediate action to address the risks associated with heatwaves. The findings reveal that certain wards are significantly vulnerable due to high land surface temperatures (LST) and elevated population density. To mitigate the impacts of heatwaves on these affected communities, the Patna Municipal Corporation, in collaboration with local health and emergency service providers, must undertake the following proactive measures:

1. **Enhance Heatwave Monitoring and Forecasting**: Collaborate with the India Meteorological Department (IMD) to bolster forecasting capabilities for heatwaves. This includes implementing a localized heat index monitoring system that incorporates real-time data on temperature and humidity, providing a foundation for timely alerts.
2. **Strengthen Stakeholder Collaboration**: Regular meetings and workshops should be organized with local authorities, health officials, and community organizations to foster a unified approach to heatwave preparedness. This collaborative effort will ensure that all stakeholders are aligned and can efficiently share resources.
3. **Implement Community Awareness Campaigns**: Develop comprehensive awareness programs specifically targeting vulnerable populations in high-risk wards. These campaigns should educate residents about the risks of heatwaves, preventive measures, and available resources to mitigate adverse impacts.
4. **Conduct Vulnerability Assessments**: In-depth assessments should be carried out in high-exposure wards to identify specific vulnerabilities and adaptive capacities. This tailored approach will ensure interventions meet the unique needs of each community.
5. **Develop a Strategic Heatwave Action Plan**: Create a detailed action plan that outlines roles, responsibilities, and protocols for response during extreme heat events. This plan should integrate existing disaster management frameworks and incorporate input from local communities.
6. **Formulate and Test Early Warning Systems**: Establish a comprehensive early warning system that utilizes heat index thresholds to trigger response actions. Conduct simulations and drills in collaboration with emergency service providers to assess the effectiveness of these systems.

By adopting these measures, Patna can significantly enhance its capacity to respond to heatwave events, ensuring that vulnerable populations are better protected and informed. This proactive approach will ultimately reduce human suffering and economic losses associated with extreme heat, fostering a resilient and adaptive community.