Urban Expansion and Climate Change: Spatio-Temporal Analysis of Land Use and Land Cover Changes in Ranchi City, India

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Abstract
This study investigates the spatio-temporal changes in land use and land cover (LU/LC) in Ranchi City from 1999 to 2024 and evaluates their impact on the climate. Satellite imagery from LISS III Resourcesat 1 (NRSC) and LANDSAT 7 (USGS) for the years 1999, 2004, 2009, 2014 and 2024 were utilized. A supervised image classification approach using maximum likelihood classification (MLC) was employed to generate LU/LC maps. To assess the accuracy of these classifications, 400 sample verification points were selected through purposive random sampling.

The results indicate a consistent increase in built-up areas, alongside a continued decrease in forest cover, agricultural land, water bodies and open spaces. This transformation underscores significant shifts in land use patterns and provides insights into their potential impacts on local climate dynamics.

Keywords: Land use/Land cover, Supervised image classification, Maximum likelihood classification, Urbanization, Climate change, Ranchi city.

Introduction

Land use and land cover (LU/LC) changes are crucial for understanding urban development and environmental transformations. Ranchi City, as the capital of Jharkhand, India, has seen significant urbanization over recent decades. These changes in LU/LC have potential implications for local climate conditions, making it essential to analyze these transformations and their effects.

Geospatial technology primarily refers to Geo-informatics, which encompasses Remote Sensing (RS), Geographic Information System (GIS) and Global Positioning System (GPS)[6,7]. Various scholars have defined this term differently. For instance, Prasad et al[5] described it as the collection, integration, management, analysis and presentation of geospatial data, models and knowledge that support disciplinary, multidisciplinary and transdisciplinary research and education[1].

The major components of geospatial technology include:

1. Collection and processing of geospatial data,
2. Development and management of a geospatial database,
3. Analysis and modeling,
4. Development and integration of logic and computer tools and software for the first three tasks.

"Geoinformatics is the combination of RS and GIS"[1,6,7]. The focus here is on spatio-temporal changes in land use and land cover (LU/LC) and their impact on climate. Urbanization drives the growth of cities, which are not abstract entities but social organisms where non-agricultural activities like production, consumption and control occur. These activities give rise to institutions and social systems distinct from those in rural areas. The interplay between these activities and social systems constitutes the process of urbanization. Urbanization, therefore, involves the transformation of society, accompanied by significant geographic, economic and social changes[9].

Land use and land cover are fundamental structures for assessing the Earth's surface to monitor ecosystem functioning. LU/LC changes, driven by natural and human activities, lead to deforestation, global warming, biodiversity loss and an increased risk of natural disasters such as flooding[2-5]. LU/LC data are crucial for environmental modeling, carbon cycle monitoring, hydrology, global climate change analysis, natural resource management and policy-making[10]. Moreover, they play a vital role in identifying groundwater prospect areas. Various LU/LC features such as vegetation cover, agricultural land, forests and grasslands, significantly influence groundwater prospects.

Rapid urbanization, with its increase in impermeable surfaces, reduces the infiltration of rainwater and surface water while areas like watersheds, riverbeds and water bodies tend to have higher groundwater prospects. The study aims to analyze spatio-temporal changes in LU/LC in Ranchi City from 1999 to 2024 and to assess the impact of these changes on the local climate, focusing on temperature trends.

Study Area

Ranchi city is located at the coordinates 23°22'N latitude and 85°20'E longitude, on the northwest bank of the Subarnarekha river within the Chhotanagpur plateau. It is situated at an altitude of 651 meters above mean sea level and is crossed by the Tropic of Cancer. Ranchi is renowned for its pristine natural environment, including lush forests, hillocks and picturesque lakes.

As defined by the Ranchi Municipal Corporation (RMC), the area of Ranchi city covers 177.19 square kilometers and is divided into 55 municipal wards as of the 2011 census. The

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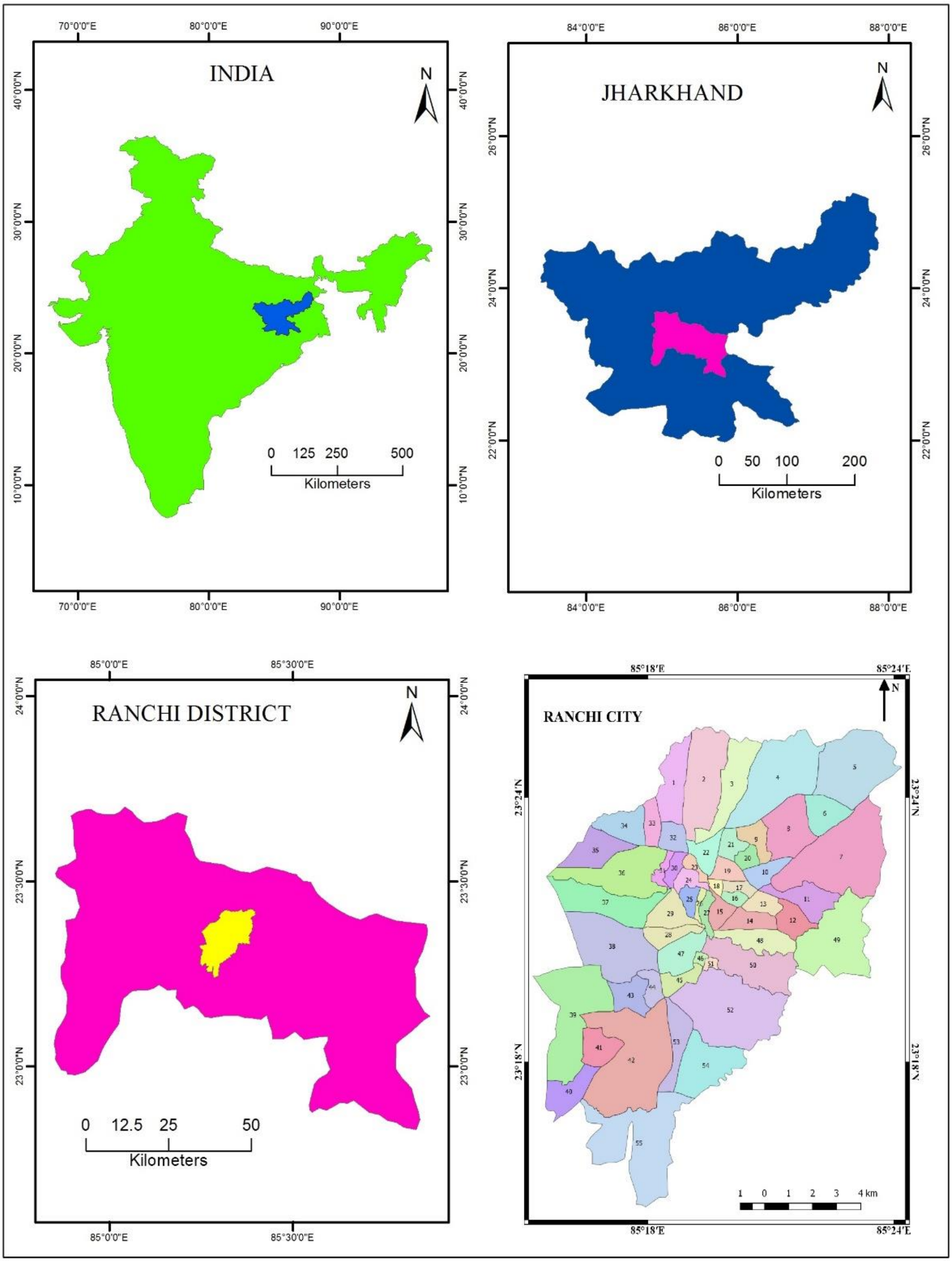
population of Ranchi city grew from 847,093 as per the 2001 census to 1,073,440 as per the 2011 census. Among the 96 cities and towns in Jharkhand state, Ranchi is the third-largest city.

The city has experienced rapid urban growth and its diverse landscape and climatic conditions make it a valuable case for analyzing spatio-temporal changes in land use and land cover (LU/LC) and their impacts on climate.



Map 1: Map showing the location of the study area
Source: Survey of India and Ranchi Municipal Corporation, further layers prepared by GIS

Material and Methods

To conduct this research, satellite imagery from LISS III Resourcesat 1 (NRSC) and LANDSAT 7 (USGS) from five different years (1999, 2004, 2009, 2014 and 2024) was analyzed. A supervised image classification approach using Maximum Likelihood Classification (MLC) was applied to generate land use/land cover (LU/LC) maps. To assess the accuracy of these classifications, 400 sample verification points were selected through purposive random sampling. This method ensured that different land cover categories were well represented in the accuracy assessment.

Data Collection

1. Meteorological Data: Historical temperature data (1981-2024) was sourced from the India Meteorological Department (IMD). This dataset includes average monthly and yearly temperature records for Ranchi along with extreme temperature events.

2. Satellite Imagery: Landsat and other Earth observation satellite images were utilized to examine LU/LC changes over the past 30 years. The analysis focused on tracking the expansion of built-up areas and the decline of green spaces.

3. Urban Planning Records: Municipal planning documents and land use maps from Ranchi's urban development authorities were reviewed to understand infrastructural changes and urban sprawl patterns.

Data Analysis Techniques

- **Land Use and Land Cover Analysis**: GIS software was used to analyze satellite imagery and to classify land cover types such as vegetation, water bodies and built-up areas. Temporal analysis was conducted to assess the spatial extent of urban growth.
- **Temperature Trend Analysis**: Moving averages were analyzed to identify long-term temperature trends, focusing on average, maximum and minimum temperatures, as well as the frequency of extreme heat events.
- **Correlation Study**: To examine the relationship between urbanization and climate change, a Pearson correlation analysis was conducted using population data as a measure of urbanization and temperature data as an indicator of climate change. This analysis helped to assess how increasing population and urban expansion influenced rising temperatures over time.

Results and Discussion

Land Use/ Land Cover Changes: In the map of Ranchi city from 1999, land use and land cover are depicted, showing a clear contrast between the northern and southern parts of the city. The northern region had more extensive vegetation compared to the southern part, as people were more engaged in agricultural activities at that time. The settlement pattern was mainly compact in the central part of the city due to the availability of water and fertile land which supported widespread vegetation. In contrast, the southern and northern regions had more dispersed settlements. Areas classified as wasteland had limited water availability and sparse vegetation. The northernmost part and some areas in the southeast and southwest of the city also had larger portions of wasteland, as there were fewer industrial and commercial areas in 1999.

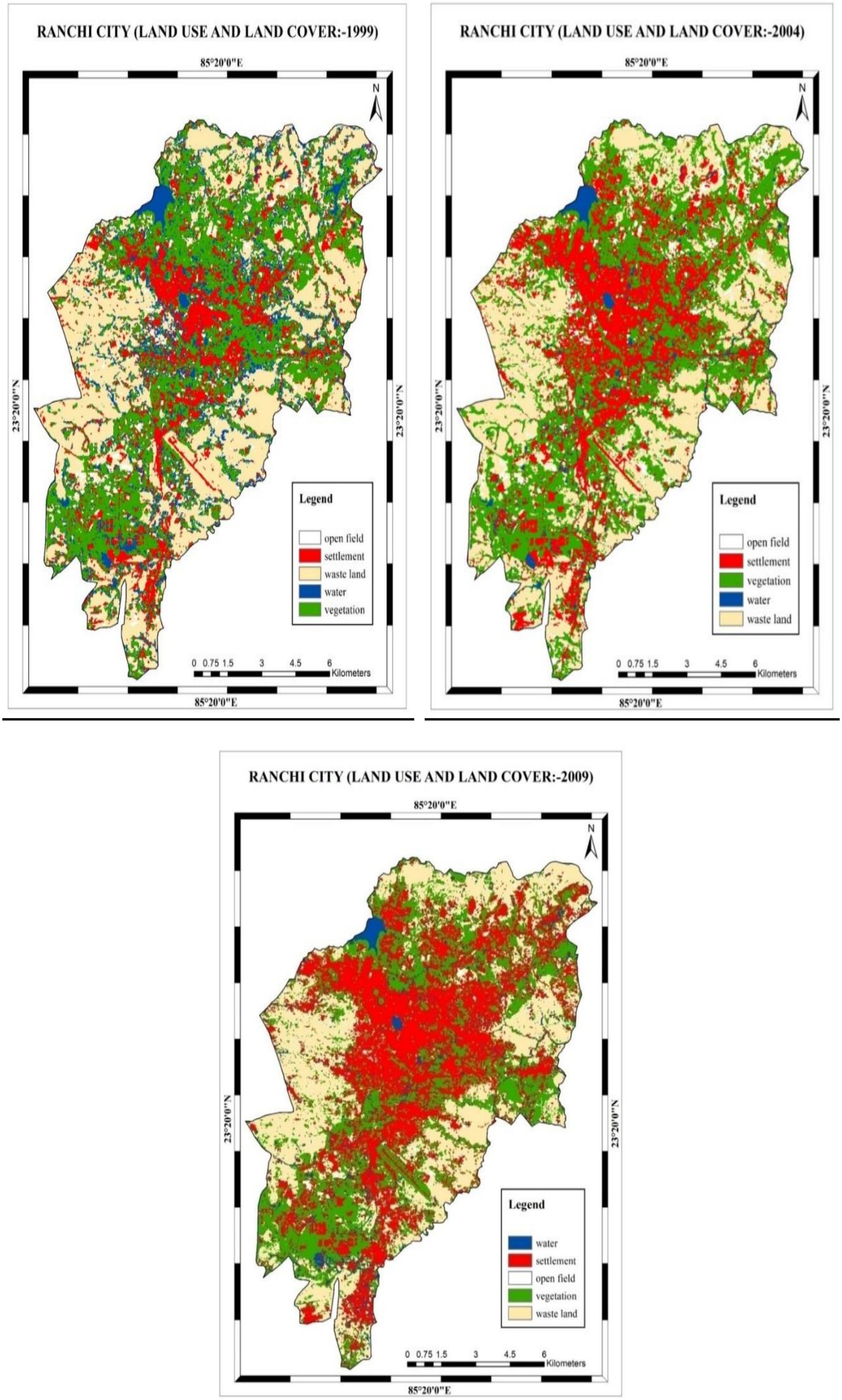
The map from 2004 shows the land use and land cover of Ranchi city, with dense vegetation still prevalent throughout the city. Notably, the southern part of the city saw an increase in vegetation compared to 1999. Settlements remained compact in the city center due to the dense vegetation and water availability, with semi-compact settlements also emerging in the southernmost part of the city. The wasteland area decreased compared to 1999, as the commercial and industrial sectors began to expand after Ranchi became the State capital. A few dispersed settlements are visible and the northern part of the city shows smaller portions of open space in some areas.

In the 2009 map, vegetation is visibly reduced compared to 2004 and 1999, primarily due to increased urbanization. Settlements remained compact, as in previous years, but the density increased. The southern part of the city saw more semi-compact settlements scattered across the area. Water bodies also diminished due to the rise in urbanization and the extent of wasteland further decreased.

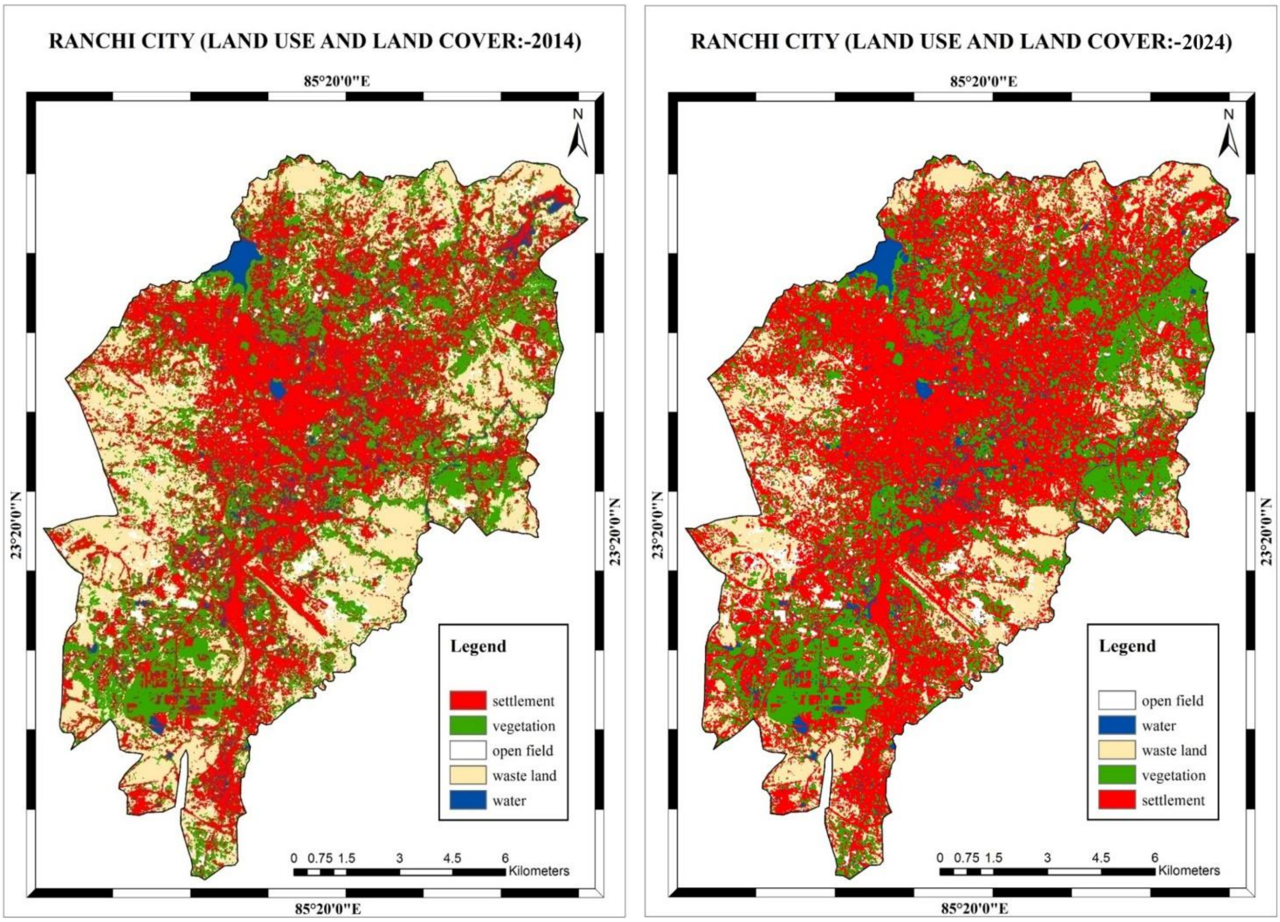
In the 2014 map, there is a noticeable decline in vegetation compared to previous years, accompanied by significant population growth, which has led to an increase in settlement areas. The settlement pattern is mainly compact in the city center, with semi-compact areas in the northern and southern parts and dispersed settlements spread across the city. Water bodies have also diminished due to the expansion of settlements. The extent of wasteland and open spaces is comparatively less than in earlier years.

The 2024 map shows a massive decline in vegetation, with the remaining greenery primarily located in the southern and eastern parts of the city. Settlements have expanded across the city, with a compact pattern in the central areas, semi-compact in the northern and southern regions and dispersed settlements throughout. Water is mainly sourced from Kanke dam in the northwestern part of the city, along with some other sources in the southern and central areas. Wasteland has largely been converted into settlements, resulting in a significant reduction in open spaces.

The analysis of satellite imagery reveals significant changes in Ranchi's land use over the past three decades. The city's built-up area has expanded by over 40%, primarily at the expense of forests and agricultural land. The city’s core has experienced the most intense development with high-rise buildings and infrastructural projects replacing open spaces. These changes align with the rapid urbanization trends observed in many Indian cities.



Map 2: Map Showing Land Use and Land Changes in Ranchi City, 1999,2004,2009
Source: Prepared from Landsat 7 Imagery, USGS



Map 3: Map Showing Land Use and Land Changes in Ranchi City, 2014,2024

Source: Prepared from LISS III Resourcesat 1, NRSC

Table 1
Extreme Weather Events in Ranchi During June (2014-2023)

Year	Temperature(°C)		Rainfall (mm)	
	Highest Maximum(Date)	Lowest Minimum(Date)	24 Hours Highest/(Date)	Monthly Total
2023	41.4 (16)	20.4 (26)	25.0 (25)	101.7
2022	40.6(09)	21.4 (23)	29.9 (22)	102.0
2021	36.2 (07)	20.5 (02)	50.4 (12)	308.5
2020	35.3 (09)	20.0 (02)	72.4 (16)	311.1
2019	41.2 (12)	19.0 (03)	34.0 (03)	124.0
2018	39.2 (18, 19)	21.4 (13)	23.1(28)	110.6
2017	43.0 (04)	19.6 (07)	46.2 (07)	172.3
2016	40.6 (11)	22.5 (01)	031.6 (24)	158.2
2015	41.0 (10)	21.7 (29)	062.6 (29)	281.7
2014	40.7(11)	22.1(01)	071.8(20)	175.8
All-time record	43.0 (04, 2017)	18.5 (07,2004)	224.3 (28,1994)	588.0 (2011)

Source: India Meteorological Department

Temperature Trends: Over the past decade, the extreme weather events in Ranchi during the month of June have shown a noticeable trend of increasing temperature extremes and fluctuating rainfall patterns. The highest maximum temperatures in June have varied significantly, with the peak recorded in June 2017 at 43.0°C, marking the all-time record for Ranchi and indicating an extreme heatwave event. Similar high temperatures were observed in 2023 and 2022, with maxima of 41.4°C and 40.6°C respectively, suggesting a recurring pattern of heatwave conditions in the region. Conversely, years like 2020 and 2021 recorded lower maximum temperatures, possibly due to higher rainfall or other meteorological factors that moderated the heat. In terms of minimum temperatures, June has shown some fluctuation as well, with the lowest recorded at 19.0°C in 2019 and the highest minimum at 22.5°C in 2016. These minimum temperatures, typically recorded during late-night or early-morning hours, reflect a relatively stable night-time cooling pattern, despite the intense daytime heat. The stability in minimum temperatures suggests that while daytime temperatures are rising, the nights remain cooler, albeit less variable.

Rainfall patterns during June have been notably erratic over the years. The 24-hour highest rainfall has varied significantly, with a peak of 72.4 mm on 16th June 2020 and a low of 23.1 mm on 28th June 2018. The highest-ever recorded rainfall in a single day for June was 224.3 mm on 28th June 1994, which far exceeds the recent figures, indicating that while heavy rain events do occur, they are less frequent in the current decade. The total monthly rainfall in June has also varied, with the highest recorded in 2020 at 311.1 mm, indicating a wetter June compared to years like 2023 and 2022, where the totals were much lower. This variability underscores the erratic nature of the monsoon, with some years bringing significant downpours and others remaining relatively dry.

Pearson Correlation Analysis: To assess the impact of urbanization on climate change, the Pearson correlation coefficient was calculated between population and temperature over multiple years. Since the normality assumption was satisfied (Shapiro-Wilk test, $p > 0.05$), Pearson correlation was deemed appropriate for this analysis.

Formula: The Pearson correlation coefficient (r) is calculated using the formula:

$$r = \frac{n\sum xy - \sum x \sum y}{\sqrt{(n\sum x^2 - (\sum x)^2)(n\sum y^2 - (\sum y)^2)}}$$

where n = 8(number of data points), $\sum x$ = 9,841,832 (sum of population values), $\sum y$=287.2(sum of temperature values), $\sum xy$ = 3.67× 10^9 (sum of the product of population and temperature values), $\sum x^2$ =1.28 × 10^{13} (Sum of squared population values) and $\sum y^2$ = 10,502.26 (sum of squared temperature values).

Substituting these values into the formula:

$$r = \frac{(8 \times 3.67 \times 10^9) - (9{,}841{,}832 \times 287.2)}{\sqrt{(8 \times 1.28 \times 10^{13} - (9{,}841{,}832)^2) \times (8 \times 10{,}502.26 - (287.2)^2)}}$$

Simplifying:

$$r = \frac{(2.936 \times 10^{10}) - (2.825 \times 10^9)}{\sqrt{(1.024 \times 10^{14} - 9.687 \times 10^{13}) \times (8.4018 \times 10^4 - 8.2526 \times 10^4) -}}$$

$$r = \frac{1.11 \times 10^9}{\sqrt{(5.52 \times 10^{12}) \times (1.49 \times 10^3)}}$$

$$r = \frac{1.11 \times 10^9}{\sqrt{8.23 \times 10^{15}}}$$

$$r = \frac{1.11 \times 10^9}{9.07 \times 10^7}$$

r = 0.935

Interpretation of Results: The analysis revealed a strong positive correlation (r=0.935), indicating that as urbanization increased, temperatures also rose significantly. The increasing population from 489,626 in 1981 to 1,523,000 in 2024 has been accompanied by a steady rise in temperature from 30.5°C to 41.4°C, demonstrating the impact of urban expansion on climate. This indicates that urbanization, particularly the expansion of built-up areas and reduction in vegetation, has contributed to rising temperatures in Ranchi city. The rapid increase in concrete structures, vehicular emissions and loss of green cover has intensified the urban heat island effect, further amplifying local climate changes.

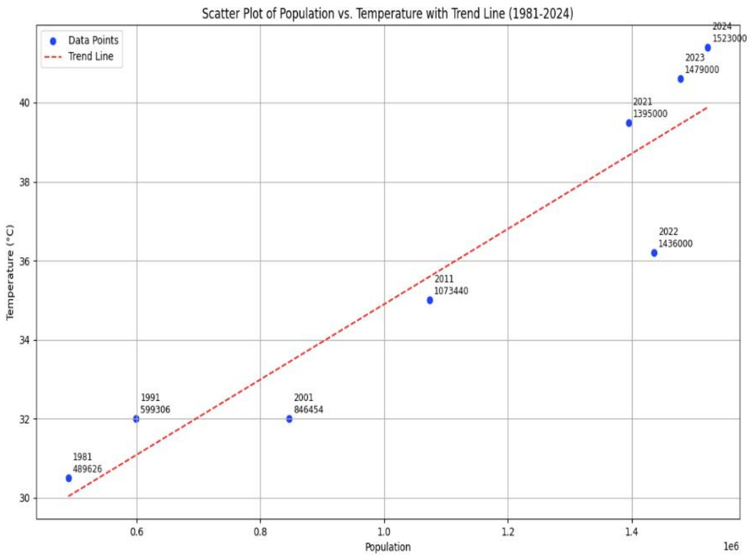


Figure 1: Scatter Plot of Population vs. Temperature with Trend Line (1981-2024)

Table 2
Population and Temperature Trends (1981-2024)

Year	Population	Temperature (°C)
1981	489,626	30.5
1991	599,306	32.0
2001	846,454	32.0
2011	1,073,440	35.0
2021	1,395,000	39.5
2022	1,436,000	36.2
2023	1,479,000	40.6
2024	1,523,000	41.4

Source: India Meteological Department

Table 3
Climatological Trends from 1981-2010

Month	Mean Temperature (°C)		Mean Total Rainfall (mm)	Mean Number of Rainy Days	Mean Number of days with			
	Daily Minimum	Daily Maximum			HAIL	Thunder	FOG	SQUALL
Jan	09.8	23.6	16.7	1.7	0.0	0.3	2.9	0.0
Feb	12.6	26.3	21.2	2.1	0.1	1.3	1.2	0.0
Mar	16.8	31.5	25.0	2.1	0.0	2.5	0.7	0.0
Apr	21.2	35.6	21.8	2.2	0.2	3.5	0.1	0.1
May	23.3	36.8	61.7	4.6	0.5	5.8	0.2	0.2
Jun	23.5	33.4	249.4	10.9	0.3	6.8	0.2	0.0
Jul	22.7	29.8	336.6	16.3	0.2	6.9	0.2	0.0
Aug	22.4	29.2	319.1	16.9	0.2	7.2	0.1	0.0
Sep	21.8	29.4	247.3	12.4	0.1	6.0	0.3	0.0
Oct	18.6	28.9	76.6	4	0.0	2.1	0.9	0.0
Nov	13.6	26.5	10.8	1	0.0	0.3	0.4	0.0
Dec	9.9	24.0	11.6	1	0.1	0.1	1.3	0.0
Annual	18.0	29.6	1397.7	75.2	1.9	42.9	8.5	0.4

Source: India Meteorological Department

Climatological Trends: Examining the climatological trends from 1981 to 2010, the mean daily minimum temperature in June was 23.5°C, while the mean maximum was 33.4°C, reflecting a moderate temperature range. Compared to recent years, these historical averages indicate a warming trend, with maximum temperatures in recent Junes often exceeding these averages. The average total rainfall for June during this period was 249.4 mm which is lower than the totals observed in wetter years like 2020 but higher than the drier years like 2023 and 2022.

The month of June typically experiences about 10.9 rainy days, consistent with its status as a monsoon month. Additionally, June has the highest frequency of thunderstorms, averaging about 6.8 days, which is in line with the onset of the monsoon and the associated unstable weather conditions. In summary, Ranchi is experiencing significant changes in its June weather patterns, characterized by rising temperatures and fluctuating rainfall. These shifts not only reflect the broader impacts of climate change but also highlight the growing need for resilience-building measures to mitigate the adverse effects on the city's infrastructure, agriculture and overall quality of life. Continuous monitoring and proactive adaptation strategies will be essential to address these emerging challenges in the coming years.

Impact of LU/LC Changes on Climate: The expansion of built-up areas and reduction in vegetation have exacerbated the warming trend observed in Ranchi. The decrease in green spaces and water bodies has reduced the city's natural cooling mechanisms, leading to higher temperatures in summer. This shift underscores the need for sustainable urban planning to mitigate the impact of urbanization on local climate.

Conclusion

This study provides a detailed analysis of the spatio-temporal changes in land use and land cover (LU/LC) in Ranchi city from 1999 to 2024 and evaluates their impact on local climate dynamics. By utilizing satellite imagery and supervised image classification, we observed a significant increase in built-up areas and a corresponding decline in forest cover, agricultural land, water bodies and open spaces. This shift reflects broader trends of rapid urbanization in Indian cities.

Our findings highlight a significant transformation in Ranchi's landscape, with built-up areas expanding by over 40% and green spaces substantially diminishing. This urban sprawl has led to a noticeable rise in temperatures, with the highest maximum temperature in June increasing by 1.9°C from 2001 to 2023 and an overall increase of 0.7°C from 2014 to 2023. These temperature rises align with the broader trend of rising temperatures observed in the region. The conversion of green spaces to built-up areas has exacerbated the urban heat island effect, intensifying temperature extremes and altering local climate patterns.

Analysis of temperature data shows a clear upward trend in both average and maximum temperatures over the past century, with a more pronounced increase in the last 40 years, coinciding with rapid urbanization. The frequency of extreme heat events has also increased, particularly during summer, correlating with the reduction in vegetation and expansion of built-up areas. Additionally, winter temperatures have risen and the frequency of cold waves has decreased compared to earlier decades.

These findings underscore the significant impact of urbanization on local climate dynamics. As Ranchi continues to grow, it is crucial to adopt sustainable urban planning and development strategies to mitigate adverse environmental effects. Incorporating green spaces into urban planning, promoting sustainable land use practices and implementing climate-responsive policies are essential for balancing development with environmental conservation. Ongoing research should continue to monitor these trends and to explore effective mitigation strategies to address the challenges posed by urbanization on climate and the environment.

Implications and Recommendations

These findings highlight the urgent need for sustainable urban planning to mitigate rising temperatures and to ensure environmental balance in rapidly developing cities. Some key strategies include:

- Increasing green cover by planting more trees and developing urban forests.
- Implementing heat-resistant infrastructure such as reflective roofing and cool pavements.
- Promoting sustainable land use planning to balance urban expansion with ecological conservation.
- Encouraging public transportation and reducing vehicular emissions to minimize heat-trapping pollutants.

By integrating these strategies, policymakers and urban planners can help to reduce the urban heat island effect and mitigate the adverse impacts of climate change on city environments.

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