Assessing Urban Heat Exposure of Precarious Settlements in São Paulo, Brazil and Delhi, India

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Abstract. *Urban heat is a growing concern in rapidly expanding cities worldwide, posing significant risks to human health and well-being. This paper investigates the hypothesis that precarious settlements characterized by inadequate infrastructure and limited resources, are more exposed to Urban Heat. Taking São Paulo, Brazil, and Delhi, India, two megacities as case studies, Land Surface Temperature (LST) is used to determine the extent of heat exposure in these settlements. In São Paulo, despite diverse locations, Cortiços and Favelas exhibit high LST values (35.80°C and 34.76°C), emphasizing challenges tied to inadequate infrastructure. Notably, industrial areas display a lower LST (32.54°C), while gated housing communities benefit from well-planned layouts, resulting in lower LST values. In Delhi, unauthorized colonies and slums experience elevated LST values (35.90°C and 35.10°C), attributed to limited vegetation and substandard housing materials. Commercial and industrial areas in Delhi demonstrate higher LST values (35.79°C and 36.38°C), emphasizing the impact of building density. The study reveals a dual nature of urban heat challenges in Delhi, with the western part exhibiting the highest LST values due to barren agricultural land post-harvest. The findings suggest that precarious settlements face higher levels of urban heat, emphasizing the need for targeted interventions to mitigate heat-related risks in vulnerable communities.*

1. Introduction

Rapid urbanization, accelerated by global population growth and exacerbated by the challenges posed by climate change, has ignited a surge in temperatures within cities worldwide. This rise in temperature has precipitated the emergence of urban heat islands (UHIs) and the intensification of heatwaves, underscoring the critical environmental issue of urban heat (Oke, 1982; IPCC, 2014). Beyond the scope of meteorological records, urban heat carries profound implications for public health and well-being, encapsulating a multifaceted challenge that transcends geographic boundaries.

While the impacts of urban heat are well-recognized, the awareness of disparities in heat exposure within cities has been an evolving narrative in recent years. Among these disparities, precarious settlements—often characterized by substandard living conditions, insufficient infrastructure, and limited access to essential resources—have emerged as hotspots of vulnerability to elevated temperatures (UN-Habitat, 2013). These marginalized communities grapple with the compounding effects of socio-economic disadvantage and environmental adversity.

This research paper embarks on an exploration into the hypothesis that precarious settlements are disproportionately exposed to urban heat, in contrast to their more privileged counterparts in residential areas. The study's primary goal was to analyze the Urban Heat Exposure in precarious settlements, comparing the realities of São Paulo and Delhi, two megacities grappling with rapid urbanization but set against contrasting socio-economic contexts. While both cities share the commonality of grappling with the urban heat challenge, the research recognizes that the dynamics and determinants of Heat Exposure in precarious settlements may vary considerably. As such, this study endeavors to unravel these intricacies and disparities, with the overarching goal of shedding light on the interplay between urbanization, vulnerability, and Urban Heat.

Understanding these disparities is not only of academic interest but of paramount significance to urban planners, policymakers, and researchers who are dedicated to formulating and implementing targeted interventions and adaptive strategies. By illuminating the factors that perpetuate elevated temperatures in precarious settlements, this research contributes to an ongoing dialogue centered on climate change resilience, social equity, and the sustainable evolution of urban spaces.

2. Materials and Methods

The research began by establishing clear objectives and defining the research topic, providing a structured framework for the study. A comprehensive literature review, with a focus on exposure from urban heat vulnerability theories, informed the development of the hypothesis and key indicators. Data collection included satellite imagery and socio-economic data, prepared for analysis through post-processing techniques. The analysis phase employed spatial analysis to unveil trends and correlations, with results presented visually through maps and figures. These representations summarized patterns of exposure. The research yielded significant findings that shed light on the complexities of urban heat exposure in the case study cities, ultimately leading to the need for mitigation strategies.

2.1. Description of the Study area

This study focuses on the urban heat exposure of Delhi, India, and São Paulo, Brazil, two cities emblematic of the challenges stemming from rapid urbanization and climate change. Delhi, India's capital, has experienced substantial urban growth, with 97.5% of its population residing in urban areas. It is situated between the Himalayas and Aravalli Mountain ranges, with a humid subtropical climate marked by scorching summers (25°C to 45°C) and winters (2°C to 22°C). The annual rainfall ranges from 400 to 600 mm. In contrast, São Paulo, Brazil's largest city and a major economic hub for South America, spans 1,521 km2 with a subtropical humid climate featuring distinct seasons. Summers (December to March) are hot and humid (25°C to 35°C), while winters (June to August) are moderate and dry (12°C to 23°C). São Paulo receives an average of 1,500 mm of rainfall annually, with the rainiest period occurring from October to March.

2.2. Materials

This research primarily relies on satellite imagery, data on precarious settlements, and Land-Use Data. The satellite imagery data from Landsat 8 was obtained from the United States Geological Survey (USGS) and NASA's Earth Observing System via the Earth Explorer platform. The location of precarious settlements and Land-uses were extracted from GeoSampa and the Delhi Urban Shelter Improvement Board (DUSIB) and Delhi Master Plan (MPD). HabitaSAMPA and MPD were utilized to categorize and define diverse types of precarious settlements in both São Paulo and Delhi. The author employed the latest available data, acknowledging that the disparate years pose a limitation. However, recognizing the enduring correlation between present-day socioeconomic conditions and those observed in the past (specifically, the year 2010 in the case of the last available census data), it is understood that this temporal gap is an inherent constraint. The study remains open to future updates pending the availability of new census data, ensuring continued relevance and accuracy.

The data collection process involves accessing and downloading publicly available datasets, which were then organized and prepared for analysis. The study was conducted at a meso-scale, covering larger sections of the cities, such as districts or clusters of neighbourhoods. In São Paulo, the analysis considered census tracts, while in Delhi, it was conducted at the ward level. This scale of analysis allowed for capturing the overall urban form, land use patterns, and infrastructure influencing heat vulnerability. The temporal scale of the study was short-term, involving the analysis of data over short time intervals. Specifically, satellite imageries for calculating Land Surface Temperature (LST) were averaged out at a two-week difference.

Table 1. Variables for Assessing Urban Heat Exposure

S.	Variables/ Indicators	Description	Data Source	Data Date	Unit, Format
1.	Land Surface Temperature (LST) – Day time	Radiative skin temperature of the land surface	Landsat 8 - United States Geological Survey (USGS) - Class 2 Level 1	Delhi: 28th April & 14th May 2022 São Paulo: 14th & 22nd Feb 2022	°C, 30 m Raster
2.	Location of Precarious Settlements	Precarious Settlements/ Slums/ Low-income areas/ Informal Settlements	GeoSampa/ Delhi Urban Shelter Improvement Board (DUSIB) /Master Plan Delhi	Delhi: 2019 São Paulo: 2010	Vector
3.	Land Use Land Cover (LULC)	How land is being used	Master Plan of Delhi 2041, SP Pvt. Company	N/A	Vector

2.3. Calculation of Land Surface Temperature (LST)

The Radiative Transfer Equation (RTE) (Yu et al., 2014) algorithm was used to calculate Land Surface Temperature (LST) from satellite images (Landsat 8 in this case). The Landsat 8 images for the case study areas were obtained from the USGS Earth Explorer website. Specific bands for these images were downloaded that capture the thermal radiation emitted by the land surface (Band 10). An ArcGIS-based toolbox developed by (Sekertekin; Bonafoni, 2020) was utilized to have the process of calculating LST automated. The toolbox takes satellite imagery and atmospheric parameters derived from NASA's Atmospheric Correction Parameter Calculator as input.

3. Analysis of Urban Heat Exposure

Urban Heat Exposure, as assessed in this study, follows the framework established by the Intergovernmental Panel on Climate Change (IPCC) on managing the risks of extreme events and disasters to advance climate change adaptation. According to this framework (IPCC, 2012), Exposure is employed to refer to the presence (location) of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected by physical events and which, thereby, are subject to potential future harm, loss, or damage.

Urban Heat Exposure in precarious settlements is a multifaceted challenge driven by various factors. To comprehensively address this issue, this research combines the analysis of land surface temperature (LST) data obtained from remote sensing with the location of precarious settlements and different land use types. By comparing LST levels in precarious settlements with other residential areas, this study aims to shed light on the complex relationship between urbanization, and heat exposure in rapidly growing cities.

3.1. Precarious Settlements in São Paulo and Delhi

Precarious settlement growth has become a symbolic representation of the complex interplay between fast urbanization, socioeconomic inequality, and inadequate housing in the cities of Delhi and Sao Paulo (Gilbert, 2018; Kundu, 2020). These so-called "informal settlements," which are sometimes known as "slums," "favelas," or "squatter settlements," are a prime example of the difficulties urban areas encounter in supporting expanding populations despite a lack of resources (Roy, 2005; Perlman, 2010). This section explores the intricate typologies of these communities that have developed within the urban framework of both cities. Different types of Precarious Settlements in São Paulo, Brazil as per HabitaSAMPA[1] are as follows –

1. **Favelas**: Favelas are characterized by precarious settlements that arise from spontaneous occupations carried out in a disorderly manner, without prior definition of lots and without street layout, in public or third-party private areas, with insufficient infrastructure networks, in which dwellings are predominantly self-built and with a high degree of precariousness, by low-income families in vulnerable situations. There are 1748 favelas registered by the Secretariat with an estimation of 399,758 households.

2. **Cortiço**: collective rental housing, and that often have shared sanitary facilities between several rooms, high occupation density, precarious circulation and infrastructure, access and common use of unbuilt spaces and very high rent values per m² built. The highest concentrations of tenements are found in the central regions of the city. 1,478 tenements registered by the Secretariat only in the subprefectures of Sé and Mooca.

3. **Loteamento:** They are the Irregular subdivisions whose occupation took place based on the initiative of a promoter and/or commercialization agent, without prior approval by the responsible public bodies or when approved or in the process of approval, implanted in disagreement with the legislation. Suffer from some type of non-compliance, such as the width of the streets, the minimum size of the lots, the width of sidewalks, and the implementation of urban infrastructure. High constructive density, lacking in trees and free

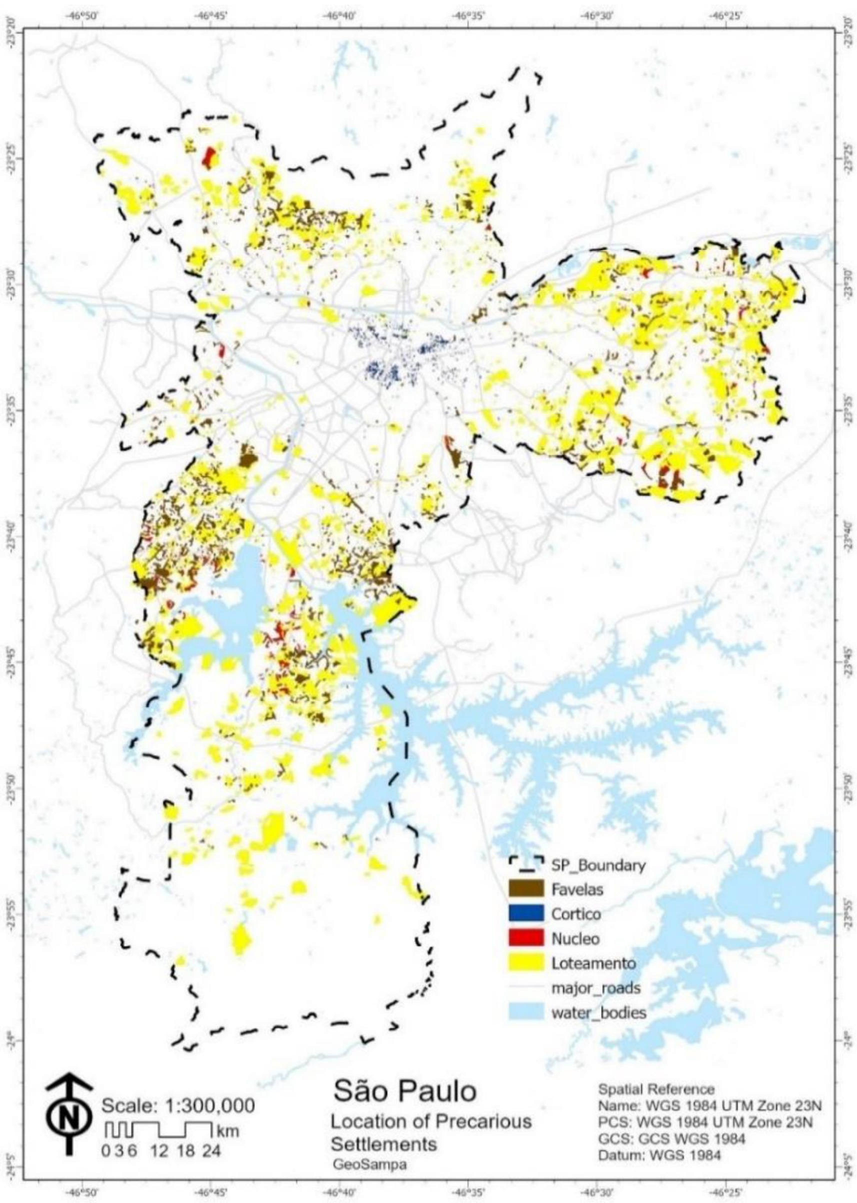

Figure 1. Precarious Settlements in São Paulo

[1] Source – HabitaSAMPA - http://www.habitasampa.inf.br/habitacao/

spaces for common use. There are 1,999 subdivisions registered by the Secretariat with an estimated 394,402 lots in irregular subdivisions.

4. **Núcleos:** Also known as urbanized centers, that are favelas equipped with 100% water, sewage, public lighting, drainage, and garbage collection infrastructure, made possible through actions by the public authorities or not. However, not yet legally regularized. There are 438 Núcleos registered by the Secretariat with an estimation of 60,638 families living in them.

Like many other rapidly expanding metropolises, Delhi's urban landscape is characterized by the growth of slums and other improvised housing. The intricate interactions between urbanization, migration, and socioeconomic inequities in the metropolis are poignantly reflected in these settlements (Kundu, 2020). These settlements highlight the difficulties metropolitan areas confront in meeting the demands of a growing population. They are characterized by inadequate infrastructure, restricted access to basic services, and poor living circumstances (Dewan & Pandey, 2017). In order to understand the distinctive qualities, spatial distributions, and underlying processes that constitute these impromptu habitation forms, this section examines numerous typologies of precarious settlements within Delhi. Different types of Precarious Settlements in Delhi as per Delhi Master Plan 2021[2,3], India –

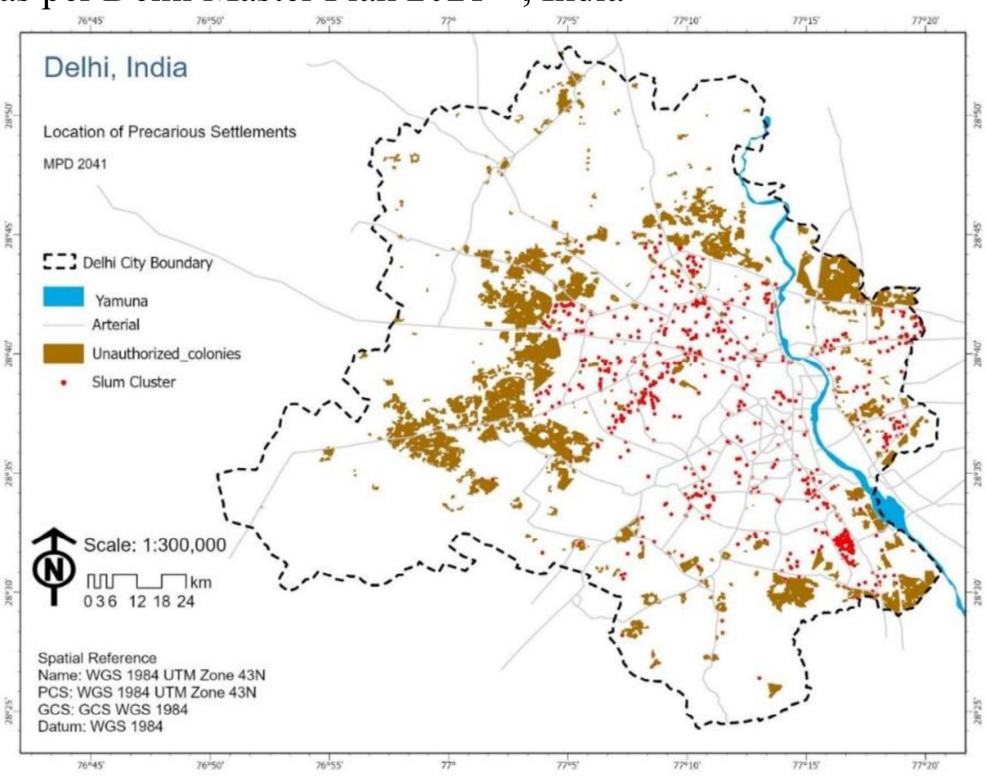

Figure 2. Precarious Settlements in Delhi

1. **Jhuggi-Jhopri (JJ) (slum) Clusters:** These non-notified slums are referred to as "squatter settlements" or "jhuggi jhopri clusters" (JJCs), and are situated on public land owned by a government body like the Delhi Development Authority (DDA), the Railways, the Central Public Works Department (CPWD), or one of the Municipal Corporations of Delhi—that has been occupied and expanded upon without authorization. These settlements are thus frequently referred to as "encroachments" in official discourse. In Delhi, these are the slum kinds that are most prevalent and well-known. The inhabitants dwell in improvised huts or shanties made out of leftover materials. JJC tenants have the least stable housing conditions and are most at risk of being demolished or evicted. Despite government entities making attempts to enhance service in these communities, JJC residents do not clearly have a right to basic amenities. The Delhi Urban Shelter Improvement Board (DUSIB), which oversees JJCs, published a set of statistics in 2014 based on a socioeconomic study conducted in each JJC in Delhi, revealing 672 JJCs with 304,188 jhuggis, or around 10% of Delhi's population, and 8.85 km^2 of land, or roughly 0.6% of Delhi's area (CPR, 2015).

[2] Delhi Master Plan 2021, Delhi Development Authority - https://dda.gov.in/sites/default/files/Master-Plan-for-Delhi-2021-(updated%2031.12.2020).pdf
[3] Categorization of Settlements in Delhi, Centre for Policy Research (CPR), India, 2015 - https://cprindia.org/wpcontent/uploads/2021/12/Categorisation-of-Settlement-in-Delhi.pdf

2. **Unauthorized Colonies:** Unauthorized colonies are established either against Delhi's Master Plans or on 'illegally' subdivided agricultural land. The literature on unauthorized colonies identifies two characteristics that set them apart: first, these areas have been "illegally" divided into plots; and second, the owners of plots in these settlements have documents (typically in the form of a general power of attorney) that demonstrate some form of tenure that may be characterized as "semi-legal". Four million people were living in as many as 1639 unauthorized colonies (CPR, 2015). These settlements often lack proper infrastructure and services, as they were established informally.

3.2. Spatial Patterns of Land Surface Temperature (LST)

The Land Surface Temperature (LST) in Delhi varies across different regions. The Northern, Central, Eastern, and Southern areas experience cooler temperatures, while the Western and Southwestern regions have higher temperatures. The extreme Southwest district's agricultural region records the city's highest surface temperatures. The minimum LST and Maximum LST are 23.3°C and 51.2°C. LST distribution variations are generally influenced by different Land Use Land Cover (LULC) properties. Vegetation areas lead to lower surface temperatures, generating a cooling effect in the urban microclimate, while concrete built-up areas contribute to higher temperatures. The Yamuna River, passing through six districts, acts as a heat moderator, recording temperatures of 23.3°C with maximum water depth, and up to 28 °C due to water quality changes caused by solid waste and sand mixing.

Lakes and drains also play similar roles in moderating temperatures. A dense network of drains crosses the city (Najafgarh Drain - the largest drain in Delhi), records a surface temperature of 27.2°C in the Southwest district, while it keeps on rising to about up to 40°C in nearby agricultural fields. Natural vegetation and tree cover contribute to ecological balance by enabling a cooling effect through evapotranspiration. The northern Delhi Ridge with moderate vegetation ranges from 28°C to 30°C. Delhi is a mix of urban and rural areas. According to the 2011 census, 97% of the population is urban, with significant sections residing in rural-urban fringe areas. The expansion of built-up areas in the city indicates an increase in urban population and a shift of open areas and agricultural fields to the periphery. Concretized areas in Delhi generally experience temperatures of 30–39°C, where the Delhi International Airport is on the higher side. Areas with little vegetation and arid terrain typically have high land surface temperatures. The Yamuna River bank, rural regions in northern and southern Delhi, and rural and agricultural areas were all covered with greenery in March, keeping the temperature of the ground there low even as the air started to blow hot. But because of agricultural harvesting, this area lost its green

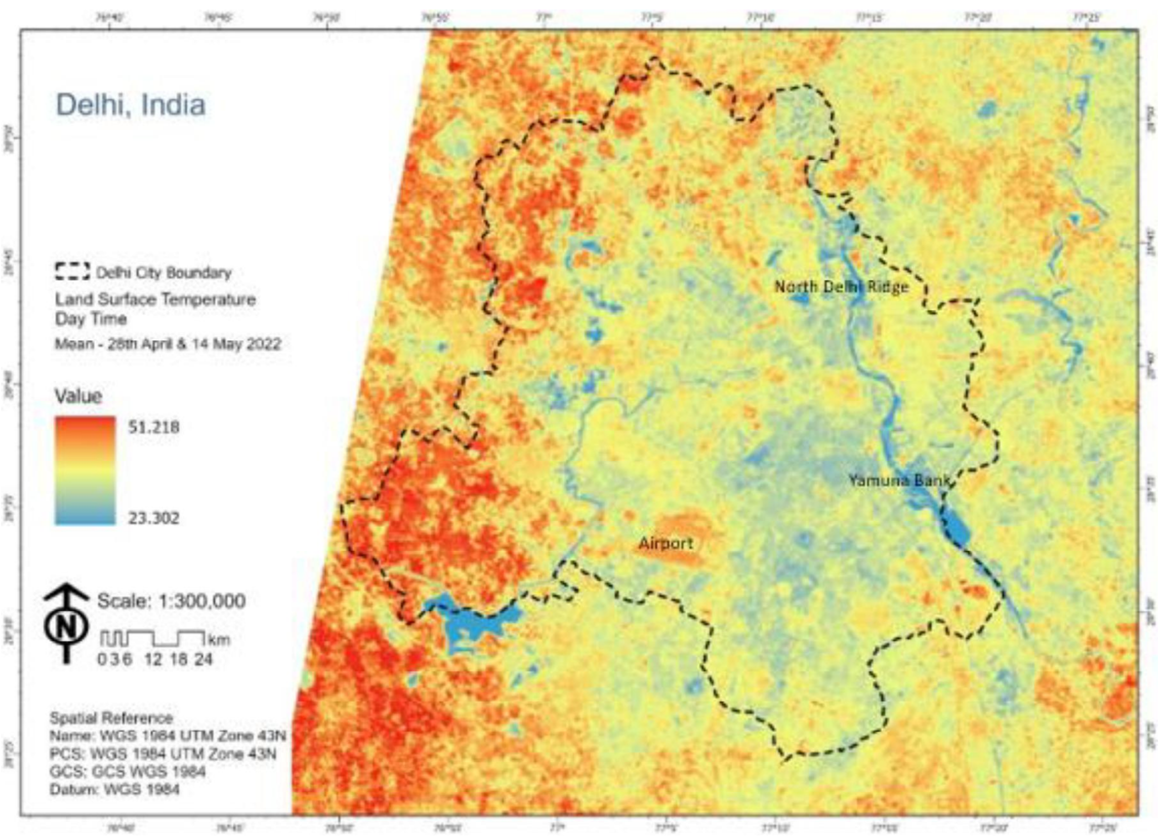

Figure 3. Land Surface Temperature (LST) in Delhi

cover in May, and the temperature of the ground there increased dramatically.

The land surface temperature (LST) of Sao Paulo, Brazil, displays prominent variations across its diverse urban landscape. As one of the largest metropolises in South America, São Paulo experiences a pronounced Urban Heat Island (UHI) effect, primarily due to its extensive concrete infrastructure. The LST ranges from a minimum of 14.79°C to a maximum of 50.20°C. Notably, the Eastern part of the city records higher LST values compared to the surrounding regions, attributed to compact low-rise buildings and a lack of green cover. In contrast, Central and South São Paulo exhibit relatively lower LST values, with high-rise buildings interspersed with open spaces and green areas. Interestingly, the shadows cast by these high-rise buildings also contribute to the cooling of the central part of the city.

There have been already efforts in place to counteract this heat buildup in the central part, which includes government buildings featuring green infrastructures like green roofs. Areas with more vegetation, parks, and open spaces tend to enjoy comparatively lower LST values, providing localized cooling effects. The LST distribution in São Paulo is shaped by a complex interplay of factors, including urbanization, land use patterns, and geographical features. Understanding these patterns is crucial for effective urban planning and climate resilience strategies amidst ongoing urban development and climate change challenges.

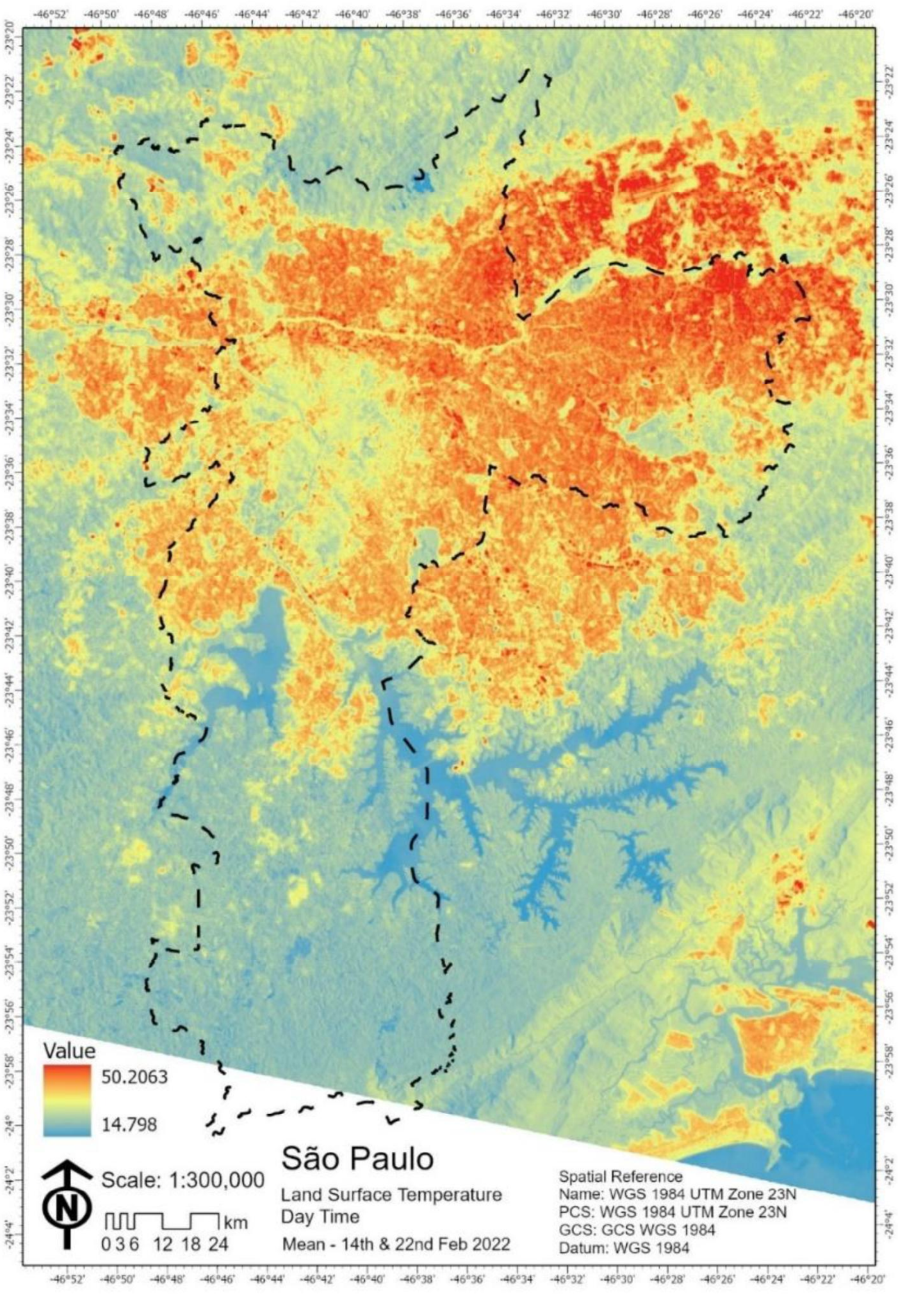

Figure 4. Land Surface Temperature (LST) in São Paulo

LST serves as a direct indicator of the thermal conditions experienced at the Earth's surface, making it a key determinant of residents' exposure to elevated temperatures. Areas with higher

LST values typically indicate hotter surface conditions, which can contribute to increased heat exposure for nearby populations. The spatial distribution of LST across an urban area directly influences the degree of heat exposure experienced by residents.

3.3. Land Use Land Cover

Land use and land cover play a pivotal role in influencing Urban Heat Exposure. The composition of urban areas, characterized by various land uses such as residential, commercial, industrial, and green spaces, significantly impacts local temperature patterns. Urban heat islands (UHIs) often form in areas with extensive impervious surfaces like concrete and asphalt, which absorb and radiate heat, leading to higher land surface temperatures (LST) (Oke, 1982). Conversely, the presence of vegetation, parks, and open spaces can mitigate LST by providing shading and cooling effects through evapotranspiration (Liu et al., 2006).

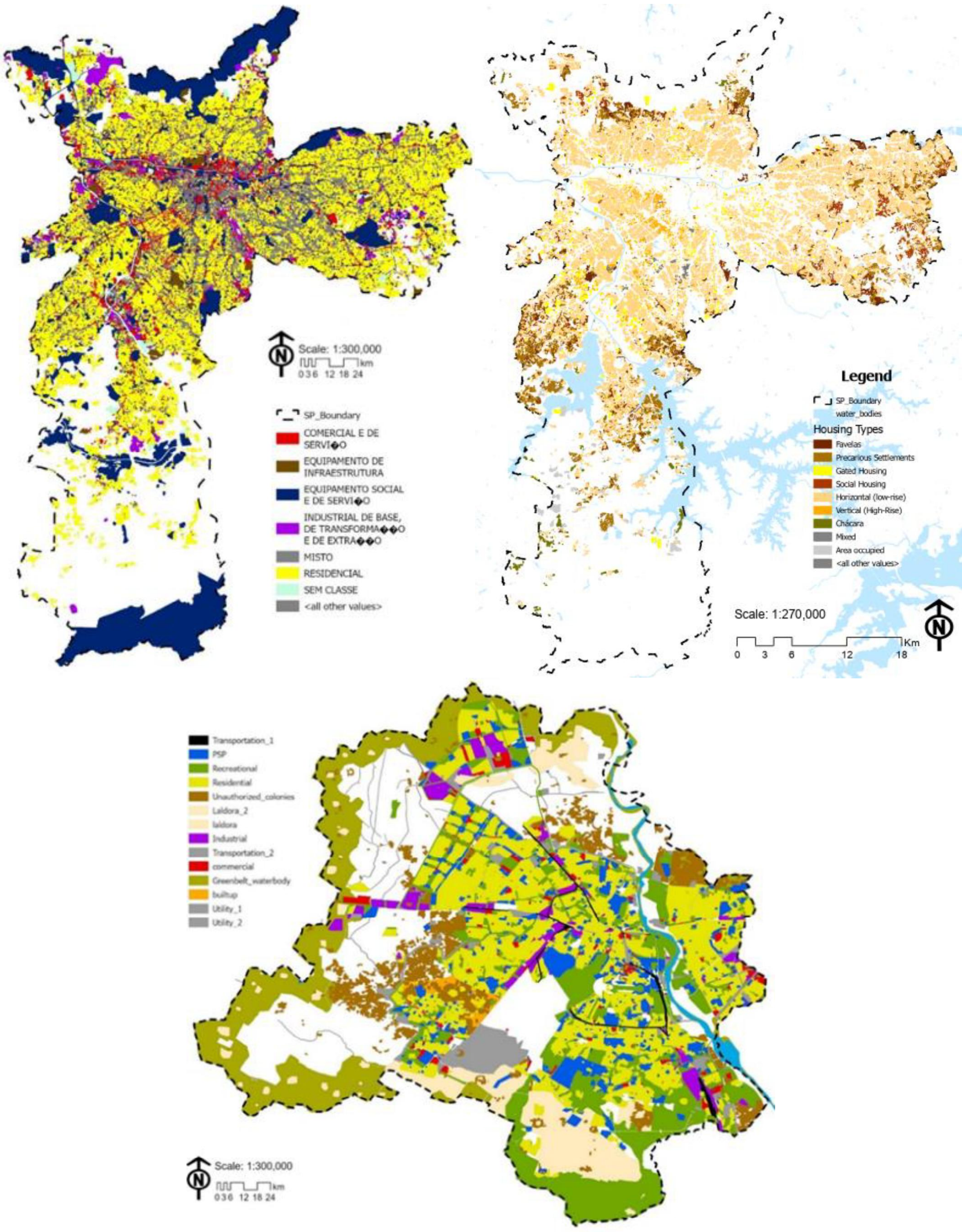

Figure 5. Land Use Land Cover - São Paulo & Delhi

4. Results

The analysis of São Paulo and Delhi demonstrates that while the underlying factors driving Urban Heat Exposure may differ in each city, they share common outcomes. In both cases, precarious settlements exhibit higher exposure to heat, highlighting the urgency of addressing this issue from a holistic perspective. The results of São Paulo unveiled a stark reality where precarious settlements experience notably higher land surface temperatures (LST) compared to formal residential areas.

In São Paulo, Cortiços, which are collective rental housing areas in the city center, often have more favorable locations and should experience lower LST compared to other densely populated areas, but it still experiences the highest LST (35.80°C). Favelas, informal settlements at the city's peripheries, also confront higher LST values (34.76°C) due to limited infrastructure, reduced vegetation, and substandard housing conditions. Loteamentos, irregular subdivisions, vary in LST based on their location and compliance with urban planning regulations, but the average LST is (34.46°C). Núcleos, urbanized centers even with improved infrastructure has a higher LST of 35.11°C. Industrial areas interestingly has a comparatively lower LST of 32.54°C and Commercial areas exhibits higher LST of 34.64°C.

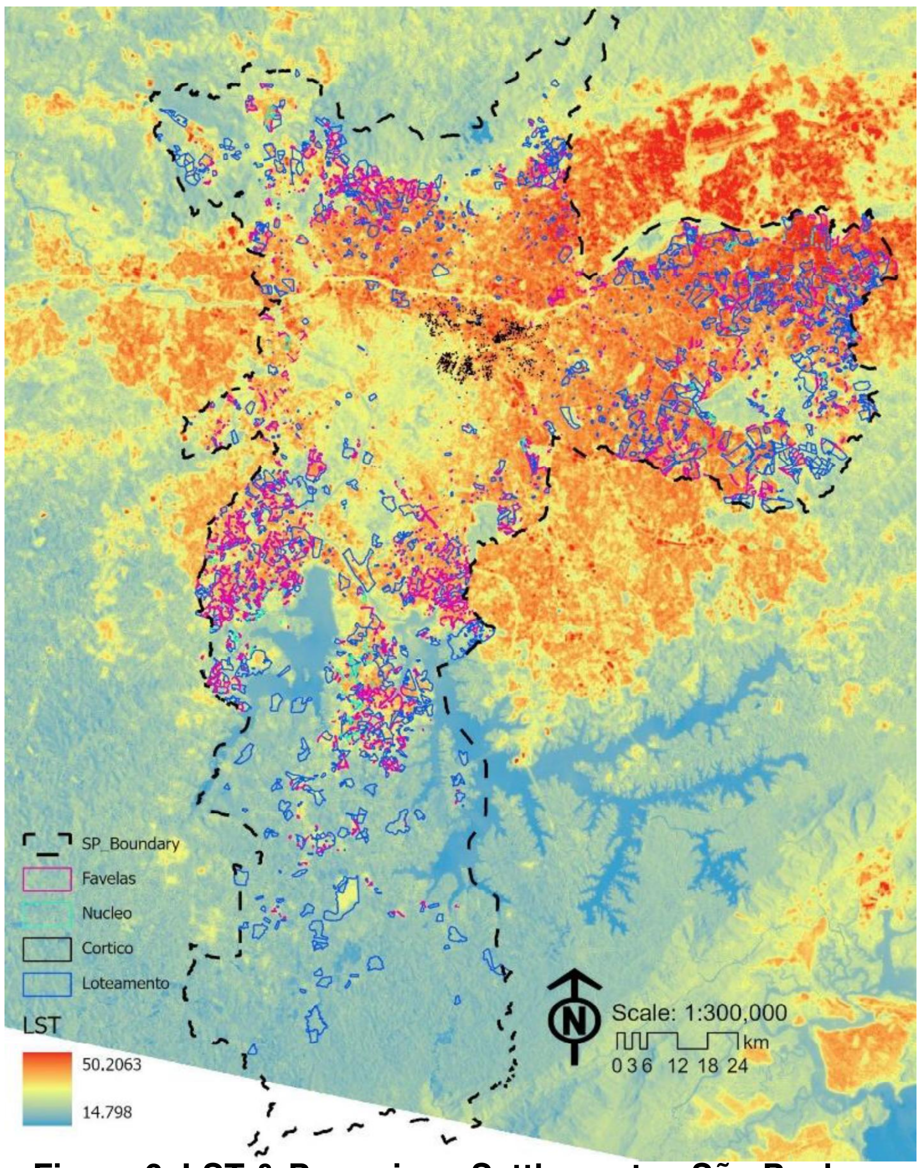

Figure 6. LST & Precarious Settlements - São Paulo

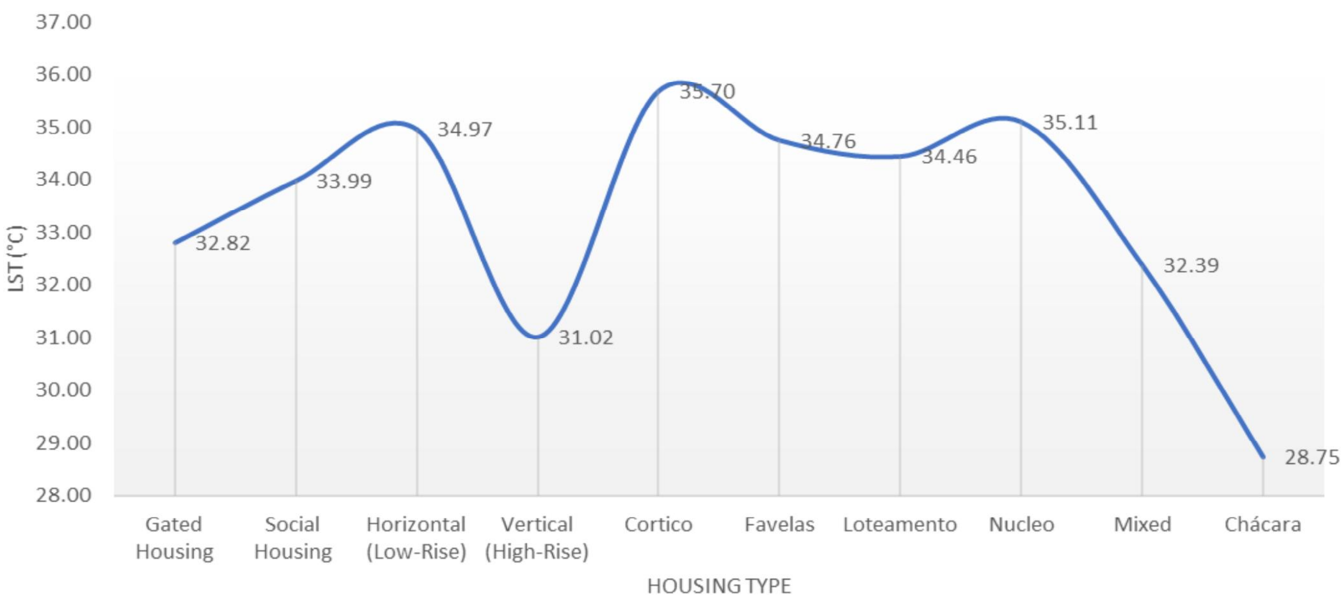

Figure 7. LST & Housing Types - São Paulo

Gated housing communities, characterized by controlled access and often lush landscaping, tend to have lower LST values due to the presence of green spaces and well-planned layouts that incorporate natural cooling elements. Social housing projects, designed to provide affordable housing solutions, display varying LST values based on factors such as location and construction quality. The mean LST experienced by social housing is 33.99°C. Low-rise horizontal housing experiences higher LST (34.97°C) due to a higher built-up area and ground coverage. In contrast, high-rise vertical housing, while offering urban density advantages, experiences a lower LST (31.02°C) due to the low ground coverage of buildings and more open or green spaces. All the different types of Precarious Settlements in São Paulo - Cortiços, Favelas, Loteamento, and Nucleo experience higher LST values. Chácaras, typically referring to rural estates or small farms, are known for their lush greenery and experience the lowest LST. Addressing urban heat vulnerability necessitates customized strategies for different housing types, particularly in densely populated areas and informal settlements.

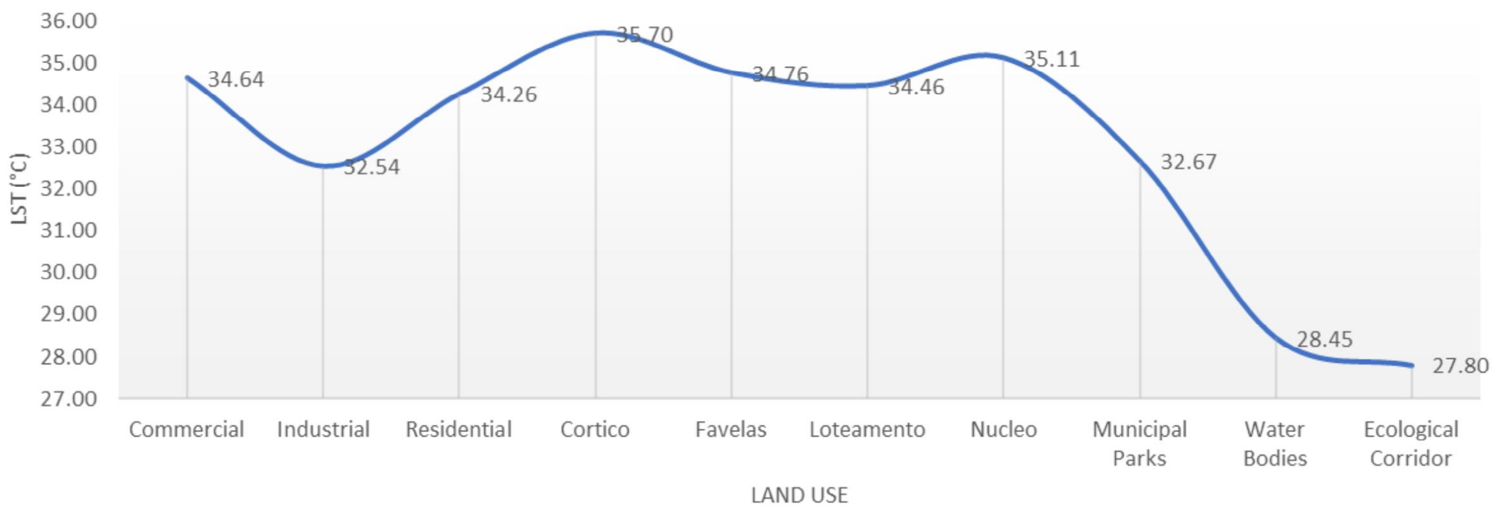

Figure 8. LST & Land Use - São Paulo

Municipal parks, water bodies, and ecological corridors contribute to cooling the urban environment. These green spaces act as heat sinks, providing localized relief from high LST values. The presence of such areas can significantly influence the thermal comfort of nearby neighbourhoods. The relationship between LST and land use underscores the critical role of urban planning, green infrastructure, and socioeconomic factors in shaping the thermal landscape of the city. Addressing urban heat vulnerability requires targeted strategies tailored to different land use types, with a focus on enhancing greenery and mitigating heat island effects.

The analysis in Delhi unequivocally demonstrates that precarious settlements are exposed to significantly higher land surface temperatures (LST), even though the highest LST values were observed in the western part of the city, primarily due to the presence of barren agricultural land post-harvest. This intriguing finding underscores the dual nature of the urban heat challenge in Delhi. The relationship between Land Surface Temperature (LST) and land use in Delhi is a multifaceted one that reflects the diverse urban landscape of the city. Commercial (35.79°C) and industrial areas (36.38°C) tend to exhibit higher LST values due to factors such as increased building density, extensive concrete surfaces, and heat generated from industrial processes. Public semi-public zones, which often include Government buildings, open spaces and parks, typically have lower LST values (33.86°C) as they provide greenery and shade, contributing to local cooling. In residential areas, LST varies depending on the presence of green spaces, building materials, and housing density. High-density residential areas with limited vegetation experience elevated LST, while residential neighbourhoods with ample greenery tend to be cooler. The average LST in Residential Areas is 34.42°C.

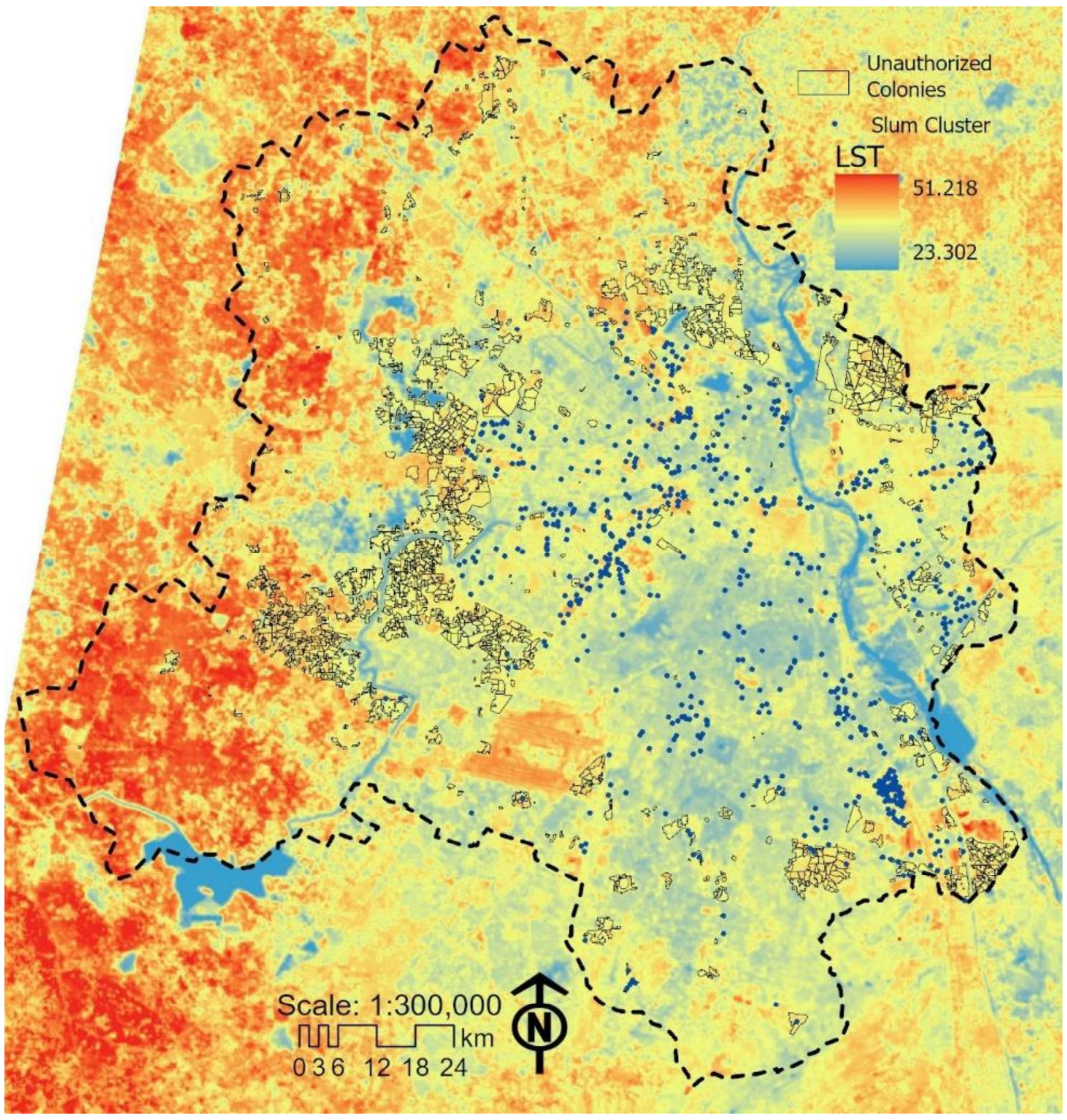

Figure 9. LST & Precarious Settlements - São Paulo

Unauthorized colonies and slums, which are often characterized by substandard housing and limited access to amenities, faces higher LST values (35.90°C and 35.10°C) due to reduced vegetation and building materials that retain heat. Water bodies, including rivers and lakes, have a cooling effect on their surroundings, leading to lower LST values in these areas. They act as heat sinks, absorbing and dissipating heat, thus providing localized cooling in the urban environment.

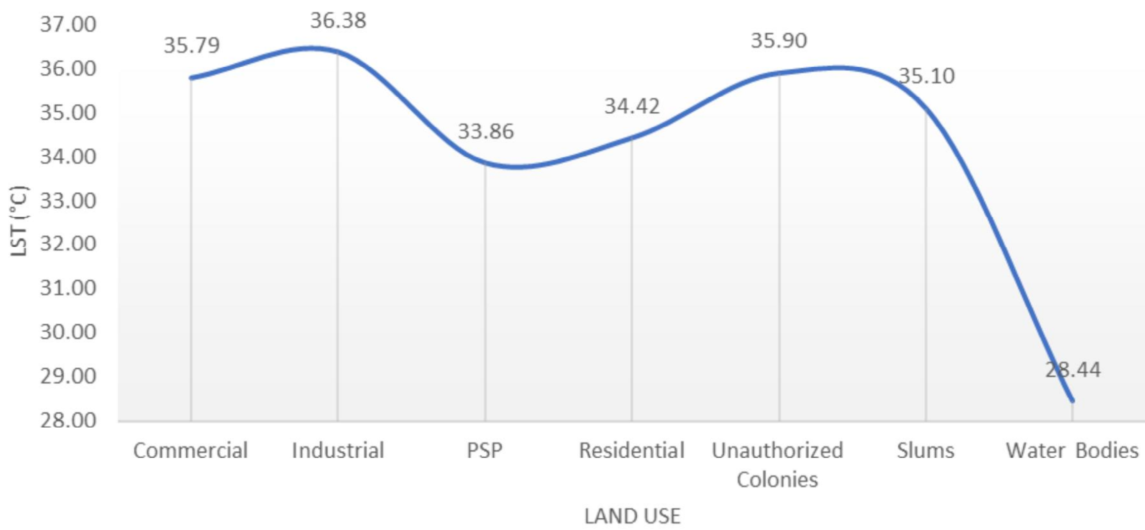

Figure 10. LST & Land Use - Delhi

5. Conclusions

The marginalized communities, characterized by inadequate infrastructure, limited resources, and substandard living conditions, face a disproportionately elevated risk of Urban Heat Exposure. The findings from this study not only confirm the hypothesis that precarious settlements are more exposed to urban heat but also underscore the urgency of tailored interventions.

This research has significance beyond academia. It strongly connects with urban planners, policymakers, and researchers who are trying to create fairer cities. There is a need to come up with specific plans that focus on the health and strength of the people most impacted by urban heat problems. In the quest for cities that can handle climate change and remain sustainable, this study shows why it's crucial to deal with the differences in how urban heat affects different people. It's about making our cities fairer and more sustainable for the future.

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