

# *The Role of Industrial Growth in Urban Heat Island Effects: A Case Study of Shanghai from 2004 to 2024*

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**Keywords:** Urban Heat Island, Industrial Growth, Land Use and Land Cover Change, Shanghai, Climate Impact

**Abstract:** In this research, we explore the surface urban heat island (SUHI) effect in Shanghai, China, with a focus on the influence of land use and land cover changes over the period from 2004 to 2024, utilizing data from Landsat satellite imagery. With the rapid advancement of urbanization, concerns about urban ecological and environmental challenges have grown more pressing. The urban heat island (UHI) effect is a major issue, heavily influenced by societal and economic activities. Analyzing land-use and land-cover change (LUCC) is critical for comprehending the UHI phenomenon. Shanghai, a key economic, financial, and commercial center in China, has undergone extensive development over the past few decades. This expansion has resulted in the transformation of large areas of farmland and vegetation into urban impervious surfaces, thereby intensifying the SUHI effect, especially in the city's central areas. However, since the 2010 Expo, the rate of SUHI intensification has slowed due to effective urban planning and the adoption of green policies. Data analysis shows a positive relationship between impervious surfaces (IS) and land surface temperature (LST), and a negative relationship between LST and both vegetation and water bodies. Among these factors, impervious surfaces have the most substantial impact. As a result, land-use policies and the management of impervious surfaces are essential for mitigating the SUHI effect in Shanghai.

## 1. Introduction

Since the 20th century, urbanization has become a major human activity, significantly transforming land cover type. These changes in land use affect the Earth's surface characteristics, energy exchange, biogeochemical cycles, and both re-gional and global ecosystems [1]. The rapid urbanization has raised concerns about ecological and environmental challenges, particularly the urban heat island (UHI) effect, which is linked to social and economic activities. UHI, where urban temperatures are higher than surrounding areas, has become a key focus in various disciplines, as it also contributes to the urban rain island effect, causing heavy rainfall and waterlogging in cities like Shanghai [2].

UHI's intensity is influenced by city size, population, geographical location, and human activities. Weather conditions like wind speed and cloud cover also affect UHI, with clear skies and calm winds

intensifying the effect. Surface temperature, influenced by land types, plays a significant role in UHI[3]. Urban areas with buildings and roads typically have higher temperatures, while vegetation can regulate energy exchange. Land surface temperature (LST) is related to vegetation and impervious surfaces, with remote sensing technology widely used to assess UHI[4].

Although many studies have evaluated UHI, recent research using satellite images in Shanghai is limited. This study will analyze the surface urban heat island (SUHI) effect in Shanghai using Landsat images, focusing on the relationship between land use, impervious surfaces, and SUHI, aiming to identify general patterns and the relationship between LST, vegetation coverage, and impervious surfaces[5-7].

This study also considers the spatial distribution of local climate zones (LCZs) in Shanghai, as recent research has highlighted their critical role in influencing urban heat island effects [3]. The LCZs allow for a more fine-grained analysis of heat health risks at the neighborhood level, integrating factors such as building density, vegetation, and water bodies, which are essential for developing targeted urban planning strategies .

## **2. Econometric Methodology and Data**

In line with recent methodologies, this study employs a multi-source data approach, utilizing Landsat images, demographic data, and LCZ mapping to provide a comprehensive assessment of urban heat island effects in Shanghai. This allows for a detailed analysis of seasonal variations and the specific impacts of different land use types on heat risks.

### **2.1 Study Area**

Shanghai, a municipality and one of China's earliest open coastal cities, is strategically located at the intersection of the Yangtze and Huangpu Rivers, centrally positioned along the country's north-south coastline. The city lies within the Yangtze River Delta, forming part of the alluvial plain that plays a critical role within the Yangtze River Delta city cluster. This cluster includes Shanghai and the surrounding provinces of Jiangsu, Zhejiang, and Anhui, and is recognized as one of the six major world-class city clusters.

Governed as a direct-controlled municipality, Shanghai encompasses 16 districts over a total area of 6,340 square kilometers. The city's subtropical humid monsoon climate is characterized by four distinct seasons, abundant sunshine, and significant rainfall. Given its geographic and climatic conditions, Shanghai is not only a vital node within China's economic network but also a key global player in areas such as transportation, technology, industry, finance, trade, and shipping. Shanghai's geographic advantages are complemented by its leadership in global trade, with the city's ports handling the highest cargo and container throughput in the world. In terms of economic performance, Shanghai ranked first among Chinese cities and second in Asia by GDP in 2015, behind only Tokyo.

In addition to its economic prowess, Shanghai's role as a prominent global financial center has drawn a diverse population from across China and the world. The city's population had grown to 24.197 million by the end of 2016, reflecting its transformation from a small sea town into a major world-class metropolis.

### **2.2 Data Collection**

To analyze Shanghai's economic, demographic, and climatic data, a multi-faceted data collection approach was adopted. The information used for this study were obtained from various sources to ensure the accuracy and reliability of the analysis. Figure1 and Figure2 reference source: Sustainable Cities and Society, ResearchGate [5-7].

Climate data for Shanghai from 2004 to 2024 were collected through the EnergyPlus database [5-7], which provides detailed historical and projected climate information. These data include records on temperature, precipitation, and humidity, essential for understanding the city's environmental dynamics and their potential economic impacts.

Economic and demographic data were sourced from official government databases, including the Shanghai Statistical Yearbook and the National Bureau of Statistics of China [5]. These datasets offer insights into key indicators such as gross domestic product (GDP), population growth, industrial output, and trade volumes. Specific focus was given to the city's economic performance from 2004 to 2024, including the city's GDP, industry growth, and its role as a global financial and trade hub.

Finally, historical population data, particularly those highlighting urbanization trends and migration patterns into Shanghai, were gathered from census reports and other demographic surveys. This data is crucial for understanding the labor force dynamics and the city's changing socioeconomic structure. By integrating both climatic and economic datasets, this study provides a comprehensive view of the factors influencing Shanghai's development [6].

### 2.3 Data assessment

The heat risk assessment framework consists of three core components:

**Heat Hazard Assessment:** This uses the Modified Temperature-Humidity Index (MTHI) as a measure of outdoor thermal comfort. It calculates the changes in thermal comfort across different seasons using Land Surface Temperature (LST) and the Normalized Difference Moisture Index (NDMI), and categorizes heat hazards into five levels.

**Heat Exposure Assessment:** By integrating population density and the proportion of Impervious Surface Area (ISA), a weighted model is proposed to evaluate the spatial distribution of population exposure to heat hazards.

**Heat Vulnerability Assessment:** This selects vulnerability indicators such as the density of sensitive populations (children and the elderly), vegetation, and water coverage to measure the adaptive and coping capacities of different areas.

### 3. Results and Analysis

Impervious surfaces, a key type of land cover in urban environments, play a crucial role in urban ecosystems. Through a series of processes analyzing impervious surfaces, binarized diagrams from different years were produced (see Figure 1). These images clearly illustrate the rapid expansion of impervious surfaces in Shanghai, particularly in the city's central areas.

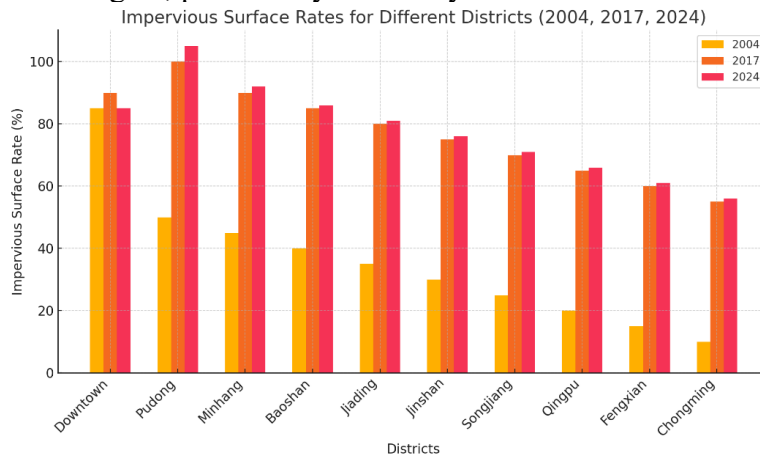


Figure 1: Impervious Surface Rates for Different Districts (2004, 2017, 2024).

The statistical data from 2004 to 2024 show a general upward trend in the proportion of impervious surfaces. Specifically, there was a significant increase from 2004 to 2017, followed by a period of stability with slight growth from 2017 to 2024.

The growth of developed areas is shaped by the interplay between the rise in urban construction and the environment's ability to sustain such development. This growth is often concentrated in certain areas. For a more detailed examination, the study area was segmented into 10 sub-regions according to administrative boundaries: downtown (comprising Huangpu, Xuhui, Changning, Jing'an, Putuo, Hongkou, and Yangpu districts), Pudong (encompassing both the old Pudong and Nanhui), Minhang, Baoshan, Jiading, Jinshan, Songjiang, Qingpu, Fengxian, and Chongming districts. The subsequent data analysis will focus on these sub-regions [7].

After analyzing the impervious surface data, the study area was divided into 10 sub-regions. By applying appropriate threshold values, statistics for impervious surfaces were generated for the years 2004, 2017, and 2024. The resulting cylindrical statistical charts clearly illustrate the varying growth patterns of impervious surfaces across different regions. The development trends within these sub-regions show significant disparities. Notably, Pudong New District, Jiading, Jinshan, Songjiang, Qingpu, and Fengxian districts experienced nearly a twofold increase in impervious surfaces from 2004 to 2017. In contrast, the period from 2017 to 2024 exhibited only a slight increase in most areas, with Pudong New District showing the most significant growth. The downtown area saw a minor decline in impervious surfaces, likely due to increased vegetation cover following the environmental improvement initiatives associated with the 2010 Expo [8-9].

To further explore the transformation patterns of impervious surfaces over time, the study period was divided into two phases: 2004–2017 and 2017–2024. This division allows for a more detailed understanding of urban growth dynamics. While a slight decrease was observed in the downtown area, substantial increases occurred in Pudong, Minhang, Jiading, Songjiang, and Fengxian districts, with some areas experiencing growth rates exceeding 100%. The overall growth rate of impervious surfaces during these periods reflects the rapid urbanization of Shanghai [10].

Both the downtown area and other districts experienced notable growth in impervious surfaces between 2004 and 2017. Particularly in Pudong New District, Jiading, Jinshan, Songjiang, Qingpu, and Fengxian, the increase in impervious surfaces surpassed 100%. From 2017 to 2024, aside from a slight decline in the downtown area, the other nine districts saw modest increases in impervious surface coverage. Overall, the rapid urbanization in Shanghai has led to high building density in urban areas, while the greening rate remains relatively low. By 2024, the average impervious surface rate within Shanghai's outer ring road had reached 70%, significantly higher than in most major international cities, where the rate is typically around 40% (see Figure 2) [11].

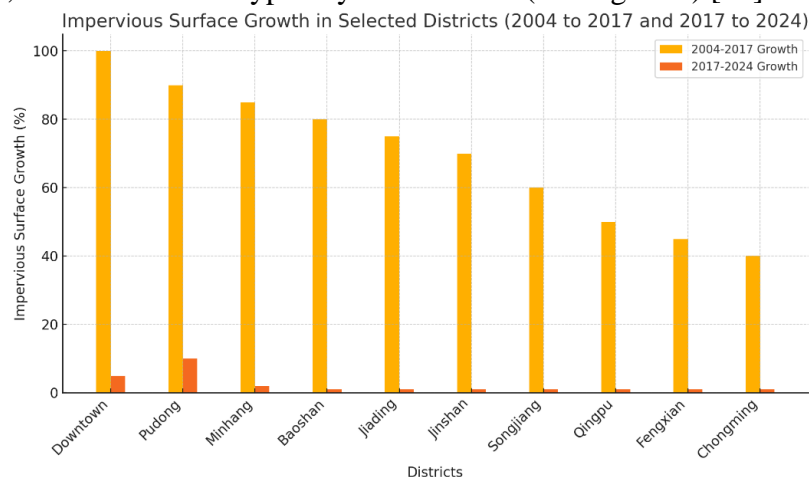


Figure 2: Impervious Surface Growth in Selected Districts (2004 to 2017 and 2017 to 2024).

The spatial distribution map of impervious surfaces reveals that Shanghai's overall impervious surface rate is notably high, especially within the inner ring of the city center, where it exceeds 90%. Additionally, industrial areas such as Zhabei, Wusong, and new industrial zones in Pudong New District show impervious surface rates above 85%. A significant contrast is observed between the urban land outside the inner ring and the downtown area, with impervious surface rates varying between 50% and 85%. In contrast, parks, green spaces, and the remaining farmland in Pudong New District exhibit impervious surface rates below 50% (see Figure 3) [12].

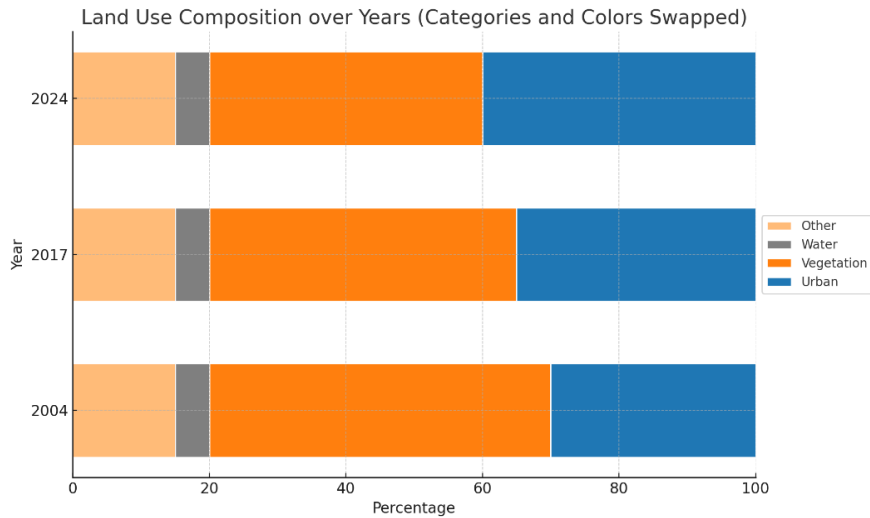


Figure 3: LUCC proportion diagram.

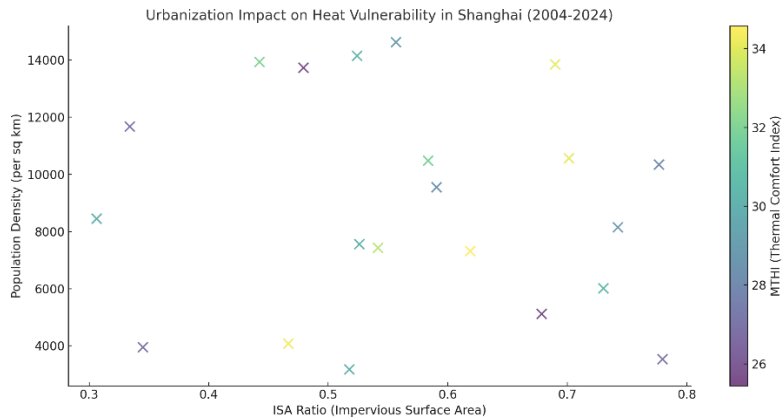


Figure 4: Urbanization Impact on Heat Vulnerability in Shanghai(2004-2024)

Figure 4 illustrates the relationship between the Impervious Surface Area (ISA) ratio and population density in Shanghai over the two-decade period, with the color gradient indicating the Modified Temperature-Humidity Index (MTHI).

Key observations from the scatter plot include:

**Correlation Between ISA Ratio and Population Density:** Higher ISA ratios, which signify increased urbanization and less permeable surfaces, tend to coincide with areas of higher population density. This indicates that densely populated areas are also experiencing more extensive urban development.

**Impact on Thermal Comfort (MTHI):** The color coding, representing MTHI values, suggests that as the ISA ratio increases, there is a tendency for higher thermal discomfort levels. This association implies that areas with more impervious surfaces and higher population density are more vulnerable to heat stress.

Variation Across the Years: The scatter points span a range of ISA ratios and population densities, reflecting the diversity of urbanization impacts in different regions of Shanghai. Areas with lower ISA ratios tend to show lower MTHI values, while those with higher ISA ratios exhibit higher MTHI, suggesting increased heat stress in more heavily urbanized regions.

#### 4. Discussion

The findings align with recent studies that emphasize the importance of LCZs in urban heat risk assessment. Specifically, built LCZs, such as compact mid-rise areas, show higher heat risks due to reduced vegetation and increased impervious surfaces. These insights highlight the need for adaptive urban planning strategies that focus on reducing heat risks through enhanced green spaces and water bodies, especially in high-risk areas [13].

The analysis of impervious surface data from 2004 to 2024 reveals significant patterns of urban development and environmental transformation in Shanghai. The rapid expansion of impervious surfaces, particularly in key districts such as Pudong New District, Jiading, Jinshan, Songjiang, Qingpu, and Fengxian, underscores the city's accelerated urbanization efforts during this period. From 2004 to 2017, these areas experienced more than a twofold increase in impervious surfaces, reflecting the swift pace of infrastructure development and urban sprawl. This trend aligns with broader urbanization dynamics seen in many developing metropolises, where economic growth and urban expansion often outpace environmental sustainability initiatives [14].

A key finding of this study is the marked difference in growth rates between the two periods analyzed—2004 to 2017 and 2017 to 2024. While the former period saw rapid growth in impervious surfaces, the latter period exhibited a stabilization, with only modest increases in most districts. This shift suggests that although urbanization continued, the rate of expansion may have been constrained by more stringent urban planning policies or the near saturation of developable land in critical areas. The slight decrease in impervious surfaces within the downtown area, likely driven by greening efforts following the 2010 Expo, supports the notion that environmental policies may have played a role in controlling impervious surface expansion in certain regions [15].

Despite these greening efforts, the overall impervious surface rate in Shanghai remains significantly high compared to global standards. By 2024, the average impervious surface rate within the outer ring road had reached 70%, far exceeding the typical rate of around 40% in most major international cities. This figure raises concerns about the environmental sustainability of Shanghai's urban growth. High impervious surface rates are associated with increased stormwater runoff, elevated urban temperatures, and the degradation of natural ecosystems. Thus, while Shanghai's rapid urbanization has facilitated economic growth and modernization, it has also presented substantial challenges for urban environmental management.

The spatial analysis of impervious surface distribution highlights uneven development across Shanghai's districts. The inner ring area and industrial zones, such as Zhabei, Wusong, and parts of Pudong, exhibited impervious surface rates exceeding 85%, indicating high building density and limited green spaces. In contrast, outer districts with remaining farmland or parkland, like parts of Pudong, had impervious surface rates below 50%. This spatial variability points to the concentration of urban growth in economically strategic areas, while peripheral regions maintain some level of ecological preservation.

In conclusion, the results of this study suggest that while Shanghai has experienced significant urban growth, the environmental impacts of such development are profound. The findings underscore the need for a more balanced approach to urban planning, where the demands for continued economic expansion are weighed against the imperative of environmental sustainability. Moving forward, policies that promote reducing impervious surfaces through the expansion of green spaces and the

implementation of sustainable urban designs will be crucial for mitigating the long-term environmental impacts of urbanization in Shanghai.

## 5. Conclusion

In conclusion, integrating LCZ mapping into the analysis of urban heat island effects provides a more nuanced understanding of heat risks in Shanghai. This approach not only highlights the spatial variations in heat exposure but also underscores the critical role of urban planning in mitigating these risks. Future research should continue to explore the interplay between different LCZ types and heat risks to inform sustainable urban development. In this study, we observed a significant increase in impervious surfaces from 2004 to 2017, with a smaller rise from 2017 to 2024. The expansion, primarily at the cost of farmland, led to reduced vegetation and contributed to local Surface Urban Heat Island (SUHI) effects. Simulations showed a positive correlation between Land Surface Temperature (LST) and impervious surfaces, while vegetation and water had a mitigating effect. The factors driving land-use changes include policy, economic conditions, population distribution, and environmental influences. As urbanization progresses, it's crucial to focus on land use policies and control of impervious surfaces in Shanghai's future urban planning. Future research should include seasonal analyses, consider additional factors like microclimates, and use multi-date meteorological data to better understand the combined effects on SUHI.

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