**Urban Heat and Existing Policy in Small and Medium Sized Cities in South Asia: How Land Use Land Cover Change is Affecting the Heat Island Effect?**

by

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## Abstract

Rapid urbanization impacts the urban environment in many ways. Urban heat Island is one of the most important impacts created by concrete surfaces and anthropogenic activities, leading to a rural-urban temperature difference. Climate change, coupled with these land use changes, makes people vulnerable to heat in cities. South Asia, home to 7 million urban dwellers, faces extreme heatwaves which increase significantly in both intensity and frequency. This study investigates Land Use Land Cover (LULC) change in nine cities across five South Asian countries over 20 years, from 2003 to 2023, and examines the correlation between Land Surface Temperature (LST) and land types—urban, vegetation, and water. The Random Forest Machine Learning model on the Google Earth Engine (GEE) platform is used for LULC classification, with 70-120 training points for each land type for the years 2003 and 2023. The study finds that built-up areas increased in all the cities over 20 years, while vegetation, water, and other land types decreased, except in Ahmedabad, where greenery increased due to planned vegetation. The overall accuracy of the LULC change detection was high (>96%) and the validation accuracy was moderate, supporting the reliability of the LULC change detection results. The study also found that the mean annual LST has increased in all nine cities, with an average increase of 3.2°C. The Pearson R correlation analysis shows that built-up areas have the highest influence on LST in all cities. Vegetation has a medium influence in most cities, and water has little or no influence due to the limited presence of vegetation and water. This study also investigated the contents of HAPs in Ahmedabad and Bhubaneswar and compared them with the international framework suggested by UNDRR. Policy recommendations suggest risk and vulnerability assessments and long-term land use planning to reduce heat vulnerability. Additionally, a GIS-based Heat Vulnerability Index (HVI) is constructed for the Chattogram City Corporation to show the spatial disparity of vulnerable populations - identifying 5 highly vulnerable, 14 moderately vulnerable, and 21 low vulnerable wards.

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War Eagle!

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## List of Abbreviations

| | |
|---|---|
| BBS | Bangladesh Bureau of Statistics |
| CCC | Chattogram City Corporation |
| GEE | Google Earth Engine |
| GIS | Geographic Information Systems |
| HAP | Heat Action Plan |
| HHAP | Heat and Health Action Plan |
| HVI | Heat Vulnerability Index |
| IPCC | Intergovernmental Panel on Climate Change |
| LST | Land Surface Temperature |
| LULC | Land Use/Land Cover |
| NDBI | Normalized Difference Build-Up Index |
| NDMA | National Disaster Management Authority |
| NDVI | Normalized Difference Vegetation Index |
| NDWI | Normalized Difference Water Index |
| SMSC | Small and Medium-Sized Cities |
| UHI | Urban Heat Island |
| WPR | World Population Review |
| IRADe | Integrated Research and Action for Development |
| IIPH | Indian Institute of Public Health |
| OSDMA | Odisha State Disaster Management Authority |
| UDRRR | United Nations Disaster Risk Reduction |

# Chapter 1: Overview

## 1.1. Introduction

Small and medium sized cities (SMSCs) are rapidly growing in South Asia (Nair et al., 2023). Most of the resources and attention go to the big cities or megacities in South Asia like Delhi, Karachi, or Dhaka, which have over a population of 10 million people. But recent studies show that so many people are migrating to SMSCs and in some cases, they are growing faster than the megacities (Nair et al., 2023; Shrestha et al., 2023). Urban growth also results in many environmental and social issues, including the heat island effect. In this era of climate change, heatwaves are also increasing in both intensity and frequency. With longer heatwaves, mortality rates due to heat are also increasing in cities along with several public health issues, increasing energy usage, and more greenhouse gas emissions, as well as many thermal comfort issues which leads to many mental health problems (Santamouris et al., 2015). Though big cities have recently developed climate/Heat Action Plans (HAP) to better adapt to these situations and mitigate the impacts in the long term (Dwyer et al., 2022), most of the SMSCs don't have any such plans as the government and media are more focused on big cities.

Keeping these things in mind, this study explores the extent of urbanization in SMSCs in South Asia and how these land cover changes are impacting the Urban Heat Island (UHI) effect. The Land Use Land Cover (LULC) change over 20 years (2003-2023) is analyzed in nine different SMSCs in five South Asian countries using Landsat imageries and remote sensing techniques on the Google Earth Engine (GEE) platform to understand the impact in different cities with different microclimatic zones, population sizes, and also landforms (coastal/inland, hilly/flat). With each land type (urban, vegetation, water) the correlation will be analyzed with satellite-derived LST to understand the impact on surface temperature. Furthermore, this study will analyze some of the existing HAPs and how we can better plan to reduce the heat vulnerability of people.

Also, the vulnerability of people due to heat differs in different areas of a city. Poor people living in slums or working in informal sectors like construction or rickshaw pulling are disproportionally exposed to climate related risks, including heatwaves (Hussainzad & Gou, 2024). Also, people with higher education levels, well-constructed housing, or areas with more greenery have better adaptability to the heatwaves. To understand this spatial variation of heat vulnerability, a case study on Chattogram City Corporation (CCC) in Bangladesh is constructed to create a Heat Vulnerability Index (HVI) for 41 wards of CCC by merging both physical (surface temperature, vegetation area, etc.) and social (socioeconomic and demographic conditions) vulnerability indicators.

### 1.2. Background

Global urban land area has increased by 58,000 km² from 1970 to 2000 (Seto et al., 2011). Today, 55% of the global population is living in urban areas (Figure-1) and 68% are projected to be residing in urban areas by 2050 (UN World Urbanization Prospect, 2018). Rapid urbanization and population increase also come with many problems, where environmental degradation and increased greenhouse gas can cause human-induced climate change (Hardoy et al., 2013). Beyond environmental pollution, increased greenhouse gases, and increased surface runoff in urban areas, urban heat possesses a significant negative impact on people living in cities. Built-up areas absorb more heat than natural environments, and the reduction in greenery combined with extensive anthropogenic activities contributes significantly to the UHI effect (Tem et al., 2015). Due to exposure to heat, city dwellers are becoming more vulnerable to many health-related issues (Mayrhuver et al., 2018).

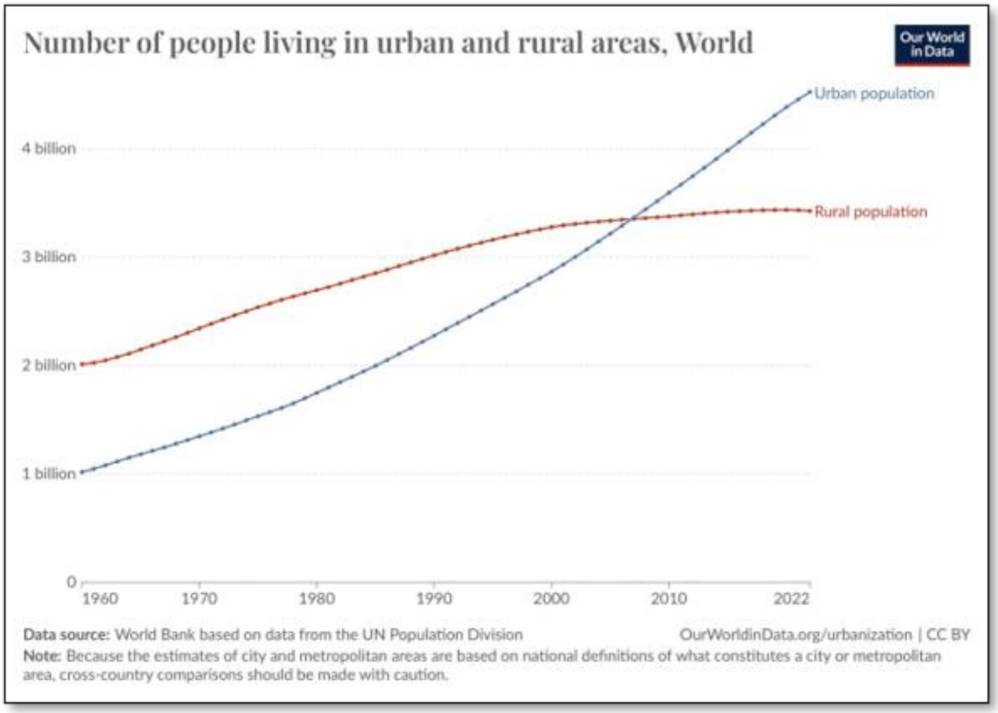


Figure 1: World Urbanization Prospect (adopted from UN Population Division, 2018)

South Asia is a topographically and historically diverse region consisting of the countries Bangladesh, Bhutan, India, the Maldives, Nepal, Pakistan, Sri Lanka, and Afghanistan. These countries are densely populated, consisting of 1.94 billion people, which is around 26% of the total global population (UN, 2019). 36% of this huge population, around 703 million people, live in urban areas which are growing by 2.4% each year (UN, 2019). Currently, this region is experiencing robust economic growth and rural-urban migration (World Bank, 2024). There are many megacities in South Asia, like Delhi, Dhaka, Karachi, Kolkata, etc., which have populations of over 10 billion. Alongside them, SMSCs are growing in these countries too because of fast economic development and easy access to urban amenities. In these cities, most of the natural surfaces like vegetation surfaces are being transformed into built-up areas, which contributes significantly to the urban heat island effect (Tem et al., 2015), and this entire condition leaves around 703 million South Asian urban dwellers at risk of extreme heat exposure (UN ESCAP, 2025). Studies conducted in major South Asian cities like Delhi, Dhaka, and Karachi have observed Urban Heat Island effects ranging from 2.5°C to 5.0°C during the summer months (Islam et al., 2024; Uddin et al., 2021; Khan & Shahid, 2024).

Keeping these soaring urban temperatures in mind, it is imperative that city, state, and federal authorities take steps to reduce the impacts of extreme heat on the residents. Many cities around the world have started creating their own comprehensive climate action plans, which address a holistic approach to all the climate risks, including heat, flood, etc., where the aim is to reduce greenhouse gas emissions (Debbage et al., 2024). The Intergovernmental Panel on Climate Change (IPCC, 2023) has reported that heat is one of the core climate risks for cities. The report also mentions that heatwaves have been increasing since 1950, and it will continue in the coming years. Now most of the global population are living in urban areas, and South Asian city dwellers are facing extreme heat risks in recent years. Newspapers in South Asia have printed numerous articles on these extreme heat conditions. According to the national newspapers, a temperature of over 52° Celsius (126°F) was recorded near New Delhi in India and Jacobabad in Pakistan in May 2024, which was the highest ever for both countries (The New York Times, 2024). Dhaka, the capital of Bangladesh, recorded 43.8 Celsius (110.8°F) in April 2024, which was the highest temperature recorded in the last 52 years (Dhaka Tribune, 2024). Nepal faced a severe heatwave in June 2024, soaring up to 45° Celsius (113°F) in Kathmandu (Asia News Network, June 2024). The highest daily maximum temperature at 38.5° Celsius (101.3°F) was recorded in Phuentsholing city of

Bhutan in 2024 (Kuensel Online, March 2024). Ratnapura in Sri Lanka recorded the highest temperature of 36° Celsius (96.8°F) in February 2024 (The Morning, February 2024).

There is an increasing need for comprehensive HAPs, as urbanization is rapidly occurring in South Asia, which increases the population's vulnerability. SMSCs are growing very fast and will soon require their own HAPs to address the needs of their expanding populations. In South Asia, SMSCs are growing for many reasons, including climate migrations and economic opportunities. However, there has been a gap in the number of climate studies done for those cities compared to bigger cities like Dhaka, Karachi, or Delhi (Youngquist et al.,2023). In South Asia, some of the SMSCs are exceeding the growth rate of megacities (Dasgupta et al., 2023). To address this gap, this research will investigate selected South Asian SMSCs; how their urbanization pattern is impacting the heat island effects, and the role HAPs can play to reduce the vulnerability of these cities.

## 1.3. Literature Review

This literature review section includes three parts based on the three objectives. First, it explores UHI-related studies in South Asia. The second section examines the HAPs and policy-related documents in the region. The third section reviews the studies that have been conducted to assess heat vulnerability in South Asia, specifically which has developed HVI.

### 1.3.1. LULC Change and UHI Studies in South Asia

Remote Sensing based studies on land type classification and the UHI effect have been increasing in recent years using LST data of Landsat or Modis. (Kotharkar et al. 2018). Studies highlight the critical relationship between LULC changes and the UHI effect across South Asia. Hassan et al. (2021) found that vegetated areas consistently maintained lower mean LST than urban cores in various South Asian cities, indicating an increasing UHI effect. Saha et al. (2021) revealed significant spatial relationships between LULC changes and LST in Eastern India's urban agglomerations, with urban expansion leading to elevated temperatures. Salam et al. (2024) demonstrated that surface urban heat island intensity increased significantly in Gazipur District, Bangladesh, due to urbanization and vegetation loss, emphasizing the need for urban greenery to mitigate heat. In Nowshera, Pakistan, Ibrahim and Nasir (2024) reported a notable increase in built-up areas and LST, advocating for improved regulation of land use changes to enhance urban resilience. Saha et al. (2020) have shown a positive correlation between increasing built up area and rising LST in India. Chatterjee et al. (2019) showed how old historical Indian districts are more prone to the UHI effect and contribute to more heat related illnesses. Deepthi et al. (2024) emphasized the rising LST in Tiruchirappalli City, India, and stressed the necessity for strategies to combat urban heat stress amid rapid urbanization. Mishra and Arya (2024) indicated substantial increases in both built-up cover and seasonal LST in Dehradun City, urging the implementation of environmental management strategies. Khan et al. (2024) projected significant urban expansion and rising LST in Peshawar, Pakistan, using machine learning models to forecast future urban dynamics and thermal impacts. Kumar et al. (2024) highlighted the importance of integrating machine learning and remote sensing to model the connections between LULC changes and urban heat, emphasizing the critical role of sustainable urban planning. Finally, Gorai et al. (2024) revealed a significant increase in built-up areas and LST in Kolkata, indicating the adverse effects of urbanization on local climates and ecological conditions.

### 1.3.2. HAPs for South Asian cities

India has been the leading country to publish the first HAPs in South Asia. The National Disaster Management Authority (NDMA) of India has developed guidelines for HAPs at both the city and district levels. Incorporating these guidelines into national climate policies has been successful in reducing mortality (Akhtar, 2023). Ahmedabad (Gujarat) in India was the first city in South Asia to adopt its HAP in 2013. Surat, also in Gujarat, followed Ahmedabad and developed its Heat and Health Action Plan (HHAP) in 2016. Nagpur (Maharashtra) developed its HAP in 2016 as well. The International Forum for Environment, Sustainability & Technology (iFOREST) reviewed 14 HAPs from cities and districts in India, finding that they were not tailored to local conditions. It also suggested that the temperature range for heatwaves should be based on perceived heat (what it "feels like"), rather than specific temperature thresholds (iFOREST, 2024). The recently developed HAP in Jodhpur, India, and the Comprehensive Climate Action Plan for Dhaka (the first city-level climate policy in Bangladesh) have incorporated the spatial dimensions of physical and social vulnerability. In Pakistan, Karachi developed its HAP after experiencing a serious heat-related disaster in 2015. In 2017, the Nepal Disaster Management Act recognized heat as a national disaster (Magotra, 2021). Sri Lanka also has a HAP under the Disaster Management Act No. 13 of 2005.

### 1.3.3. Heat Vulnerability Studies of South Asia

South Asia is highly vulnerable to heatwaves due to its geographical location, infrastructure, and socioeconomic conditions. There is an increasing trend of heatwaves in most countries, and associated mortality is also rising (Sharma et al., 2022). Many studies have focused on megacities in South Asia for vulnerability assessment (Debnath et al., 2023). Abrar et al. (2022) used Principal

Component Analysis (PCA) to normalize 26 variables and build an HVI for the 41 thanas in Dhaka Metropolitan City. Rana et al. (2022) conducted a study in Lahore, Pakistan, using a 400-household level survey and average weighted index to identify vulnerable populations. Singh (2023) applied PCA and suggested an indices method for mapping heat vulnerability in Indian urban centers. Azhar et al. (2017) created a composite HVI by applying PCA on 17 normalized variables for 640 districts in India. Adnan et al. (2024) identified vulnerable areas by calculating the HVI of five major cities in Bangladesh using the components of exposure, sensitivity, and adaptive capacity.

### 1.4. Research Questions and Objectives

In light of the discussion in the introduction, this study aims to explore the spatiotemporal relationship between land types and temperature in selected South Asian cities over 20 years between 2003 and 2023. Additionally, it will examine policy interventions and vulnerability identification in one selected city. The specific research questions are:

**RQ1**: **How does LULC change affect the UHI intensity of nine SMSCs in South Asia?**

Objective: To assess the LULC changes in the selected cities over 20 years (2003-2023) and analyze the correlation between LST and different land types (NDBI, NDVI, MNDWI).

**RQ2: How can HAPs be improved to reduce inequality in the context of increasing urban heat in South Asian cities?**

Objective: To review the HAPs of two cities (Ahmedabad and Bhubaneswar) among the nine cities to make them more spatially effective.

**RQ3: What is the spatial distribution of heat vulnerability in one of the South Asian cities?**

Objective: To develop a ward-level Heat Vulnerability Index for Chattogram City in Bangladesh as a case study.

## 1.5. Study Area

Looking at the top 500 cities by population in South Asia from World Population Review (WPR 2023, worldpopulationreview.com), nine cities have been selected from five South Asian countries based on diversity in landform (hilly/flat), location (inland/coastal), and microclimatic conditions based on Köppen's classification (Kui et al., 2021) for the first objective. None of the cities are megacities, as we are specifically looking into SMSCs (below 10 million). Bhutan was not included because none of its cities were in the top 500 list. Additionally, Colombo was initially selected as a study site in Sri Lanka, but due to the unavailability of Landsat images on the GEE platform, it had to be removed from the study area.

Below is the list and short description of each city:

| Country | City | Population | Terrain | Location | Koppen's Classification |
|---|---|---|---|---|---|
| Bangladesh | Chittagong | 5,513,609 | Hilly | Coastal | Am (Tropical monsoon climate) |
| Bangladesh | Rajshahi | 983,707 | Flat | Inland | Aw (Tropical savanna climate, dry winter) |
| India | Bhubaneswar | 1,289,254 | Flat | Inland | Aw (Tropical savanna climate, dry winter) |
| India | Ahmedabad | 8,854,444 | Flat | Inland | BSh (Hot semi-arid climate) |

| | | | | | |
|---|---|---|---|---|---|
| India | Kanpur | 3,286,142 | Flat | Inland | Cwa (Humid subtropical climate, dry winter and warm summer) |
| Nepal | Kathmandu | 1,621,642 | Hilly | Inland | Cwb (Warm-summer humid continental climate) |
| Pakistan | Quetta | 1,221,495 | Hilly | Inland | BSk (Cold semi-arid climate) |
| Pakistan | Gwadar | 51,901 | Flat | Coastal | BWh (Hot desert climate) |
| Afghanistan | Kabul | 3,043,532 | Hilly | Inland | BSk (Cold semi-arid climate) |

*Table 1: List of Cities in South Asia for the study*

**Chattogram, Bangladesh:** Chittagong is the second largest city of Bangladesh, and it is one of the major city corporations of Bangladesh. It is also the major port city of the Chittagong district. It is a coastal city located near the Bay of Bengal. The area of Chattogram City Corporation encompasses 65 square miles with a population of around 5.5 million people (WPR, 2023). As it is a highly urbanized area with a high population density and tropical monsoon climate, this area is prone to heatwaves. (Raja et al., 2023).

**Rajshahi, Bangladesh:** Rajshahi, located in west-central Bangladesh, is the fourth largest city in the country. The area of Rajshahi City Corporation is around 47 square miles, with a population of around 1 million (WPR, 2023). This is one of the most heatwave prone cities in Bangladesh with a tropical monsoon climate and high population density (Tawsif et al., 2022).

**Bhubaneswar, India:** Bhubaneswar is the capital and largest city of the state of Odisha in India, with an area of 72 square miles and around 1.2 million people (WPR, 2023). It is one of the heat prone areas with a tropical savanna climate and recently has been facing massive heatwaves (Boyaj et al., 2023).

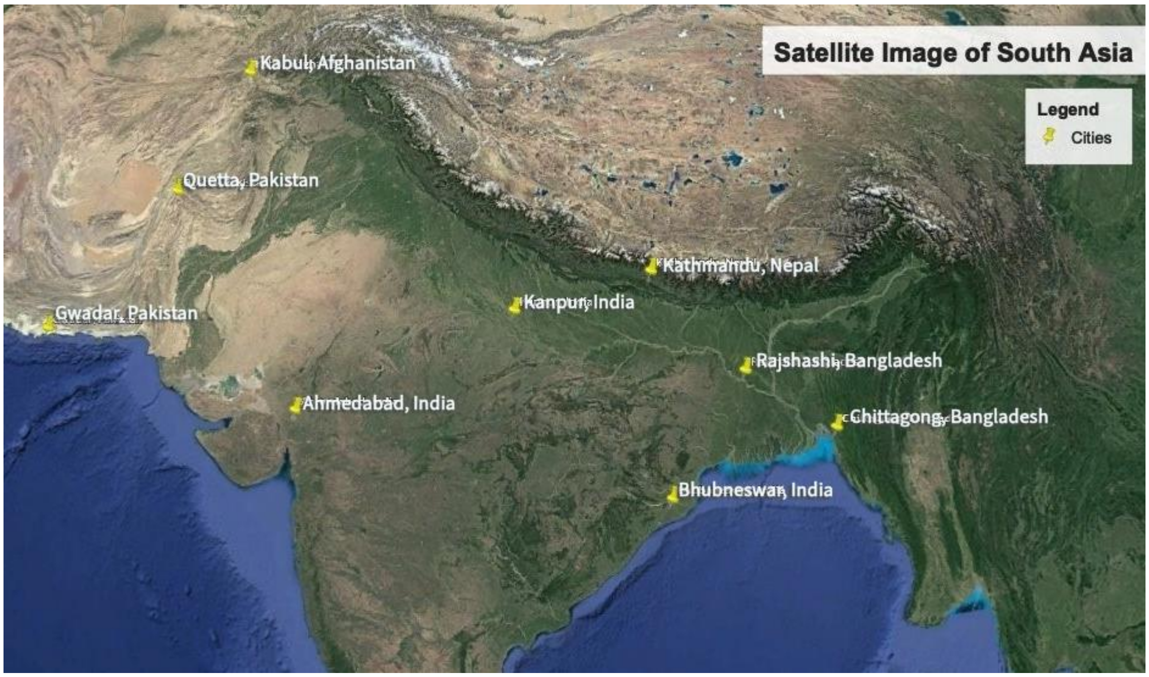


*Figure 2: Geographic Distribution of Cities across South Asia*

**Ahmedabad, India:** Located in Eastern India, Ahmedabad is the most populous city in the Gujarat state and the fifth most populous city in India, with an area of 720 square miles and a population of around nine million people (WPR, 2023). Located in a hot semi-arid climate, Ahmedabad has a high risk of heatwaves and already has an established HAP (Jaiswal et al., 2022).

**Kanpur, India:** With an area of 156 square miles and a population of around 3.2 million people (WPR, 2023), Kanpur is a populous city located in the west central part of India. It is a financial capital, heavily industrialized, and the most populous city of the Uttar Pradesh state. With a humid subtropical climate, Kanpur has experienced several extreme heat waves in recent years (Bal et al., 2022).

**Kathmandu, Nepal:** Kathmandu is the capital and most populous city of Nepal. It is located near the Himalayan hilly region at an altitude of 1,400 meters (4593.17 feet). The capital city has an area of 19.02 square miles and a population of 1.6 million (WPR, 2023). With a warm-summer humid continental climate, there is an increasing risk of heatwaves in recent years (Banjara et al., 2024).

**Quetta, Pakistan**: Quetta is the capital of the Baluchistan province and one of the major urban centers in western Pakistan. Located at an altitude of about 1,680 meters (5,500 feet) above sea level, it is surrounded by mountains, giving it a unique hilly landscape. The city spans approximately 103 square miles and has a population of around 1.2 million people (WPR, 2023). Quetta experiences a cold semi-arid climate, characterized by hot summers and cool winters, with limited rainfall, making it prone to extreme heat in summer months (Durani et al., 2021).

**Gwadar, Pakistan**: Gwadar is a coastal city located in the southwestern province of Baluchistan on the Arabian Sea. It covers an area of about 19.4 square miles and has a smaller population of around 52,000 (WPR, 2023). Known for its hot desert climate, Gwadar experiences extremely high temperatures, especially in the summer, with very little rainfall (Mongabay, 2024).

**Kabul, Afghanistan**: Kabul, the capital and largest city of Afghanistan, is situated at an altitude of about 1,790 meters (5,873 feet) in a narrow valley surrounded by the Hindu Kush mountains. The city spans around 38 square miles and has a population of approximately 3 million (WPR 2023). It has a cold semi-arid climate with cold winters and warm summers, making it susceptible to increasing temperatures and potential heat waves due to limited vegetation and rapid urbanization (Raoufi et al., 2024).

All nine cities are located in different types of landforms and microclimatic regions, and insights from the LST of the nine cities will give us a holistic idea of the current conditions of the UHI effect in South Asia.

### 1.6. Significance of the study

The IPCC Sixth Assessment Report highlights that urban areas, especially in South Asia, are becoming the changing climate impact hotspots due to rapid urbanization, population growth, and inadequate infrastructure (IPCC, 2023). Rising temperatures and intensifying UHI effects will exacerbate heat-related health risks, disrupt economic activities, and strain public health systems. This research is significant because it addresses the pressing issue of urban heat in South Asia, a region particularly vulnerable to the impacts of climate change. By quantifying the correlation between land use types and LST, this study will provide crucial insights into how urbanization influences temperature variations across nine cities of smaller populations, each with its unique microclimate and topography. There have been many studies on UHI and its correlation between different land types, but this study is unique as it focuses on SMSC of different topography and climate which can be replicated to other regions with similar background scenarios. Through this analysis, understanding UHI intensity will play a critical role in shaping and modifying policies. Identifying UHI hotspots allows city planners and policymakers to target interventions where they are needed most, such as expanding green and blue infrastructure, incorporating reflective and heat-resilient materials in urban design, and revising zoning laws to reduce heat risks.

Furthermore, this research will assess the effectiveness of existing climate and heat action plans and provide evidence-based recommendations for enhancing their implementation or proposing new initiatives tailored to urban vulnerabilities. With UHI intensity data as a foundation, this study will guide efforts to mitigate health and economic impacts while fostering urban resilience. Preparing for increasing urban heat impacts, as emphasized by the IPCC (2023), requires collective action at every level, ensuring that South Asian cities can sustain their development in the face of a warming future.

# Chapter 2: Data and Methods

## 2.1. Introduction

This section explains the data sources and methods used to answer the three research questions and objectives. In the data section, data sources are explained for each objective – remote sensing data for objective 1, policy documents for objective 2, and variables of heat vulnerability for objective 3. In the methods section, LULC change analysis and correlation analysis for objective 1 have been described. For objective 2, there was a discussion on the steps of the policy brief of HAPs. Finally, the datasets and variables for heat vulnerability, along with the steps for building HVI, are discussed for objective 3.

The entire study will be remote sensing and GIS based analysis. Supervised LULC classification and LST calculation are conducted on GEE using Landsat imageries for objective one. The HAPs of cities, along with district level and national level heat/climate policies were reviewed for object two. To address objective three, socioeconomic data from the Bangladesh Population Census – 2022 is used along with other physical indicators collected from the Bangladesh Bureau of Statistics (BBS) to calculate the Heat Vulnerability Index of Chattogram.

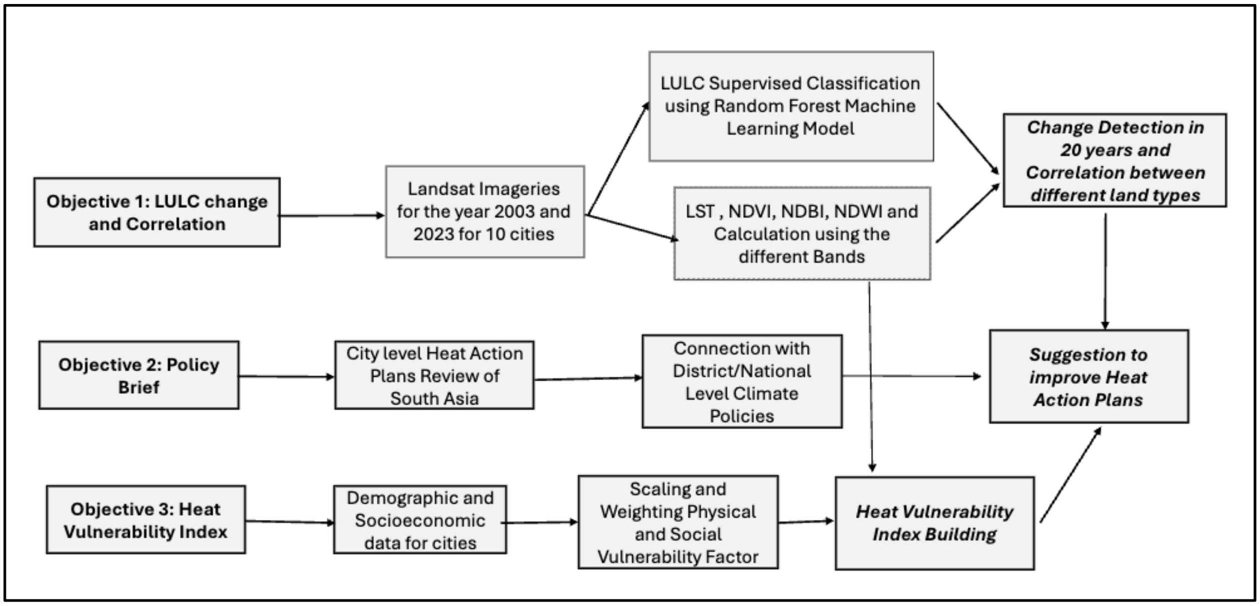


*Figure 3: Methodological Flowchart for the Study*

## 2.2. Objective 1: LULC Change and LST Calculations

**LULC Change Analysis:** Using Landsat imagery uploaded to the GEE platform, LULC maps are generated for nine cities for the years 2003 and 2023 to determine the LULC changes over 20 years. A supervised classification approach is employed using the Random Forest Machine Learning technique. For each of the four classes (Vegetation, Water, Urban, and Bareland), 70-120 random points are placed on each satellite image to train the machine learning method. Landsat 7 and Landsat 8 imagery are imported for classification of the years 2003 and 2023 on the GEE platform. Finally, land type changes over the 20-year period (2003–2023) are analyzed to observe urban growth and land use shifts.

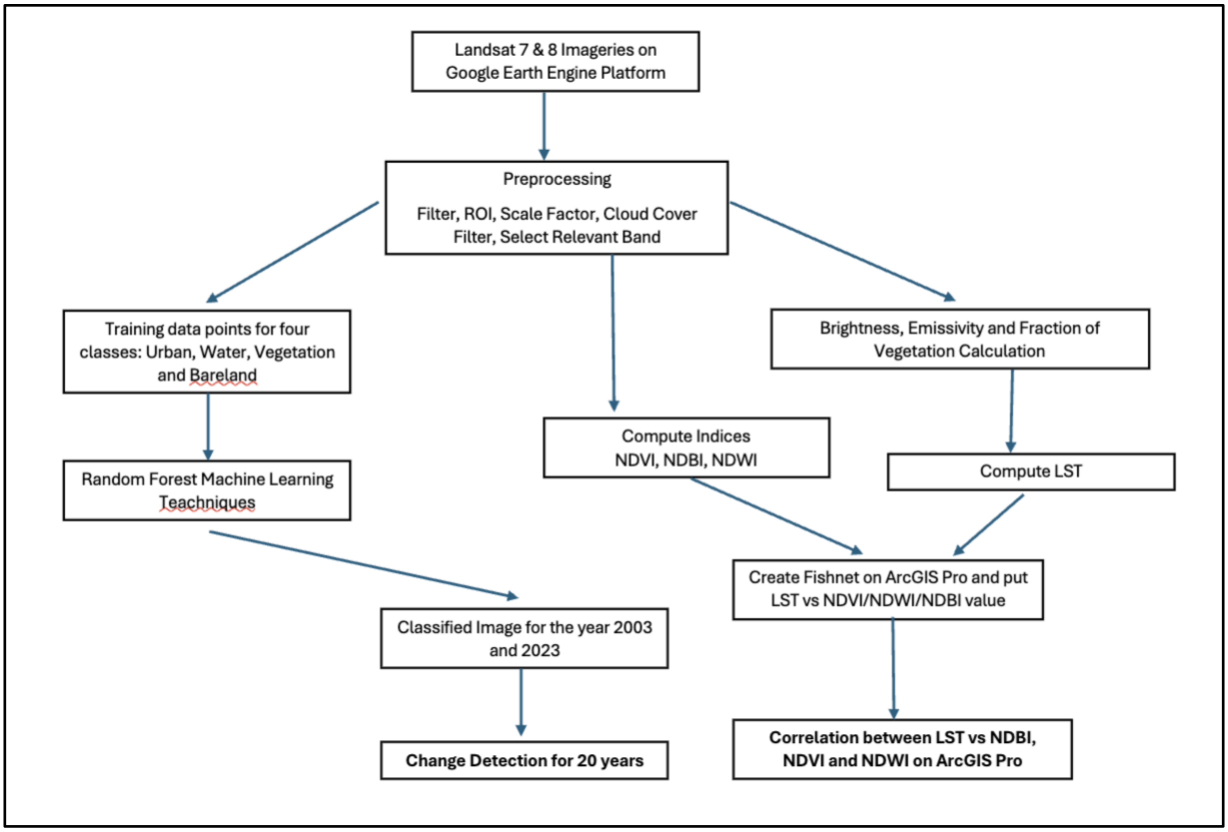


*Figure 4: Methodological Flowchart for Objective 1 - LULC Change and Correlation Analysis*

**LST Calculation:** Landsat thermal imagery on the GEE platform is used to calculate LST. First, cloud-masking and scaling factors are applied to the optical and thermal bands. Then, LST is calculated using the thermal band (Band 6 for Landsat 7 and ST_B10 for Landsat 8) and adjusted for emissivity based on NDVI-derived fractional vegetation cover (Weng et al., 2004). Here's the equation for the calculation.

$$LST = \frac{TB}{1 + (0.00115 \times (TB/0.48359547432)) \times \ln(EM)} - 273.15$$

Where:

- $TB$ = Brightness Temperature (Kelvin) from the thermal band (ST_B10), computed as:

$$TB = ST\_B10 \times 0.00341802 + 149.0$$

- $EM$ = Emissivity, calculated using the fraction of vegetation ($FV$):

$$EM = (FV \times 0.004) + 0.986$$

- $FV$ = Fraction of vegetation, derived from the Normalized Difference Vegetation Index (NDVI):

$$FV = \left(\frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}}\right)^2$$

*Figure 5: Equation for calculating LST from Landsat*

**Index Calculation for Different Land Types:** For vegetation, urban area, and water – the index is calculated using the following formulas and band combinations for Landsat 7 (2003) and Landsat 8 (2023):

| Land Type | Index Name | Equation | Band Names | Source |
|---|---|---|---|---|
| Vegetation | Normalized Difference Vegetation Index (NDVI) | $NDVI = \frac{NIR + RED}{NIR - RED}$ | Landsat 7: NIR (Band 4), RED (Band 3)<br>Landsat 8: NIR (Band 5), RED (Band 4) | Tucker et al., 1979 |
| Urban Area | Normalized Difference Built-Up Index (NDBI) | $NDBI = \frac{SWIR - NIR}{SWIR + NIR}$ | Landsat 7: SWIR (Band 5), NIR (Band 4)<br>Landsat 8: SWIR (Band 6), NIR (Band 5) | Zha et al., 2003 |
| Water | Modified Normalized Difference Water Index (NDWI) | $NDWI = \frac{GREEN - NIR}{GREEN + NIR}$ | Landsat 7: GREEN (Band 2), NIR (Band 4)<br>Landsat 8: GREEN (Band 3), NIR (Band 5) | McFeeters et al., 1996 |

*Table 2: Equations for calculating indexes for different land types*

**Correlation between LST and Land Types:** To understand the relationship between UHI intensity and LULC, Pearson's R correlation analysis is conducted to determine the positive or negative correlation, and P-values are used to understand the statistical significance. This analysis examines how variations in LULC classes—such as urban areas, vegetation, and water—correlate with LST values across the nine selected cities. 500 random points are created on the GEE platform for indices values (LST vs NDVI/NDBI/MNDWI), and then a linear graph is created from those points along with Pearson's R coefficient value and P-value.

### 2.3. Objective 2: Policy Review

Among the nine cities in this study, only Bhubaneswar and Ahmedabad have established HAPs to address urban heat challenges. To enhance the effectiveness of these plans, established HAPs from other cities across South Asian countries will be reviewed. By analyzing the strengths and weaknesses of existing plans and integrating findings from the remote sensing analysis, this study will conduct a qualitative thematic analysis of these two policies. There are several international guidelines for developing HAP. World Health Organization (2008) has a heat health action plan guideline. United Nations Disaster Risk Reduction (UDRRR, 2025) has a very recent guideline for making cities resilient to climate change. By comparing the local HAPs of two cities with the international guideline, this study will provide targeted policy recommendations aimed at improving spatial resilience to heat stress and promoting effective adaptation strategies in cities lacking comprehensive heat action frameworks, ensuring environmental justice for everyone.

### 2.4. Objective 3: Heat Vulnerability Index

Socioeconomic and demographic indicators from the Bangladesh Population Census 2022, combined with physical indicators (LST, NDBI, NDVI, and NDWI) derived from remote sensing analysis, are integrated to develop the HVI of Chattogram City Corporation. A field trip in Bangladesh was carried out to collect census information from the Bangladesh Bureau of Statistics (BBS) office. Discussions with experts to select vulnerability indicators were conducted. The following table shows the list of indicators based on sensitivity, exposure, and adaptive capacity described in the framework of IPCC (2014):

| **Dimension** | **Variable** | **Weight (%)** | **Source** | **Relevance** |
|---|---|---|---|---|
| **Exposure** | LST (Land Surface Temperature) | 30 | Landsat imagery for 2022 accessed via Google Earth Engine | Directly quantifies areas of extreme heat exposure. |
| | Total Population | 20 | Bangladesh Bureau of Statistics (BBS), Population and Housing Census 2022 | High-density areas experience intensified urban heat effects and greater human exposure. |
| | Floating Population Percentage | 5 | Bangladesh Bureau of Statistics (BBS), Population and Housing Census 2022 | Floating populations can contribute to transient increases in heat exposure, but their impact is less significant compared to permanent residents. |
| **Sensitivity** | Slum Population Percentage | 8 | Bangladesh Bureau of Statistics (BBS), Population and Housing Census 2022 | Poor housing quality limits insulation and cooling capacity, reducing resilience to heat. |
| | Illiteracy Rate | 5 | Bangladesh Bureau of Statistics (BBS), Population and | Low literacy levels can limit awareness and access to heat adaptation strategies. |

| | | | | |
|---|---|---|---|---|
| | | | Housing Census 2022 | |
| | No Internet Percentage | 5 | Bangladesh Bureau of Statistics (BBS), Population and Housing Census 2022 | Lack of internet access can limit access to information and resources for heat adaptation. |
| | Kancha Ghor (Poor Housing Percentage) | 5 | Bangladesh Bureau of Statistics (BBS), Population and Housing Census 2022 | Poor housing quality limits insulation and cooling capacity, reducing resilience to heat. |
| | No Electricity Percentage | 5 | Bangladesh Bureau of Statistics (BBS), Population and Housing Census 2022 | Access to electricity enables cooling devices, enhancing resilience. |
| **Adaptive Capacity** | NDVI (Normalized Difference Vegetation Index) | 4 | Landsat imagery for 2022 accessed via Google Earth Engine | Vegetation provides cooling, shading, and mitigates surface heat. |
| | MNDWI (Modified Normalized Difference Water Index) | 3 | Landsat imagery for 2022 accessed via Google Earth Engine | Water availability reduces heat stress and enhances local cooling. |

*Table 4: Factors contributing to Heat Vulnerability and their sources and relevance*

Each variable is normalized using the min-max method and weighted according to its importance in QGIS. The OpenQuack Integrated Risk Modelling Toolkit is installed and used for scaling and weighting variables. We add the sensitivity normalized value of the variables to the exposure normalized value and subtract the adaptive capacity variables' values. The 41 wards of CCC are categorized into low, medium, and high vulnerability according to the index value.

## Chapter 3: Results and Discussion

### 3.1. Introduction

This chapter explains the results found from remote sensing analysis and policy reviews for the three objectives. For the first objective, the LULC changes for each land type (urban, vegetation, water, bareland) across nine cities are discussed in the first subsection. LULC changes are demarcated as the percentage changes over a 20-year period (2003-2023). An important thing to remember is that all percentage changes are based on the total area. For instance, if the total area is 100x and the urban area increases from 10x to 20x, it is explained as a 10% increase in the total area rather than the 100% increase from the previous urban area. For the second section of objective one, this chapter will explain the results of the correlation analysis. The Pearson correlation coefficient (r) quantifies the strength and direction of a linear relationship between two variables (Wubante, 2020), while the p-value assesses the statistical significance of this relationship, indicating whether the observed correlation is likely due to chance (Komaroff, 2020). The relationship between the urban area and LST is explained in the LST vs. NDBI section 3.2. Also, the impacts of vegetation and water on the surface temperature are explained in the LST vs. NDVI and LST vs. NDBI subsections, respectively.

For the second objective, this chapter discusses a qualitative analysis of the existing HAPs in South Asia. Amongst the study areas, Ahmedabad and Bhubaneswar in India have existing HAPs, and these two documents were reviewed to understand effectiveness and to provide suggestions for future HAPs.

For objective three, a heat vulnerability index for the Chattogram City Corporation in Bangladesh is developed to identify the vulnerable population (section 3.4). The HVI map shows the most and least vulnerable wards among the 41 wards. The. HVI results and policy reviews from the second objective are integrated in this section to find practical solutions for reducing heat inequality in the city.

### 3.2. Objective 1

**RQ**: How does LULC change affect the UHI intensity of nine SMSCs in South Asia?

**Objective**: To assess the LULC changes in the selected cities over 20 years (2003-2023) and analyze the correlation between LST and different land types (NDBI, NDVI, MNDWI).

#### 3.2.1. LULC Change Over Time

All of the cities have shown urban growth. Kanpur in India and Kabul in Afghanistan had the highest area increases of 53.06 km² and 53.51 km², respectively. Rajshahi in Bangladesh and Kanpur had the highest percentage increases in total city area, with 29.73% and 26.03%, respectively (Figure 6). Vegetation has decreased or remained almost unchanged in all the cities except for a 48.07 km² expansion in Ahmedabad, which is an 8.4% increase in the total vegetated area. Ahmedabad city authorities have planned to increase vegetated areas, interlinkages of lakes, and increase greenery around the Sabarmati River, according to the *Ahmedabad Climate Resilient City Action Plan (2023)*. Kanpur has faced the highest decrease by area, 41.32 km², while Rajshahi had the highest percentage decrease, 19.19% of the total area. Gwadar and Kabul had a very slight increase in vegetated areas in the desert area. Water bodies were insignificant in all of the cities in both years and had little or no change. Chittagong had the highest percentage of water bodies, with about 61 km², which is around 24% of the total area in both years. Only Kanpur has seen the highest decrease of around 5% of the total area, from 4.68 km² to 1.08 km². Bareland (and all other land types except urban, vegetation, or water) has decreased in all the cities, with the highest decrease in Ahmedabad by 16.04% of the total area, decreasing from 237.87 km² to 147.89 km².

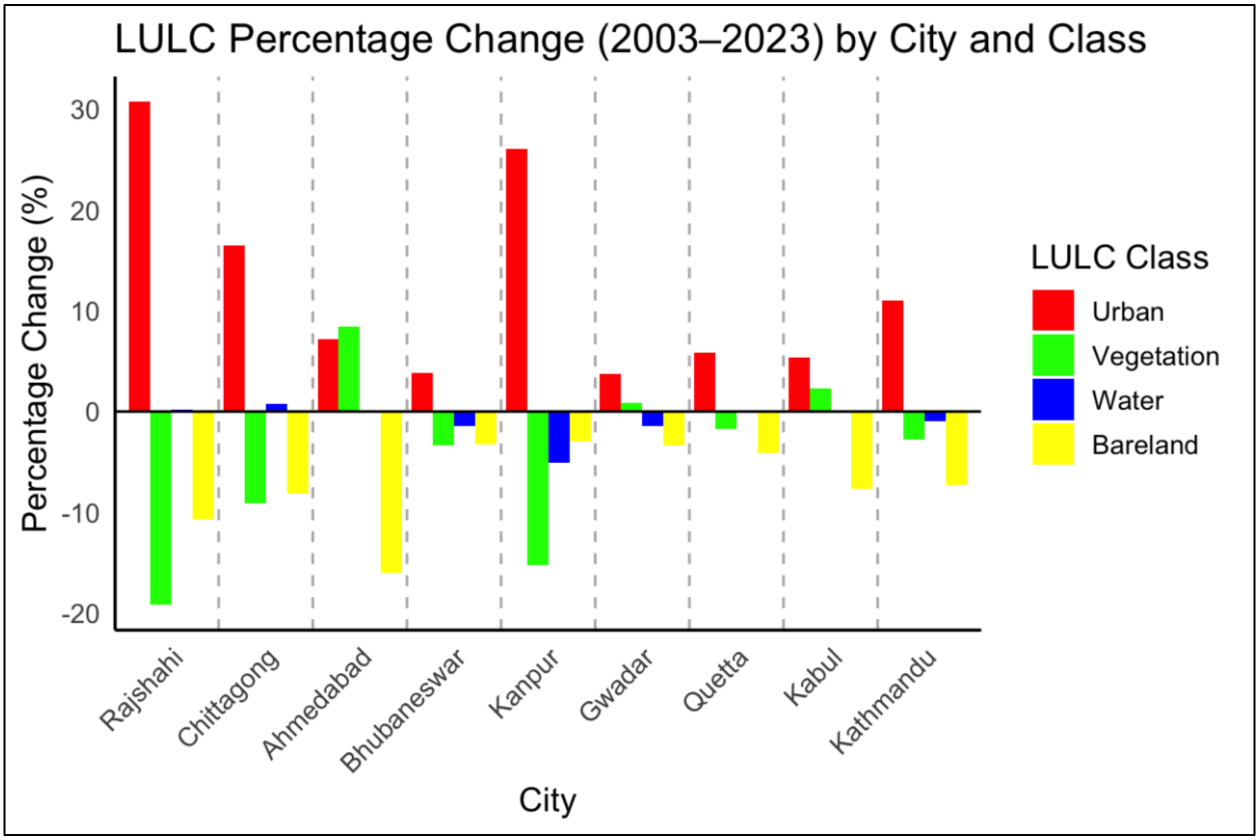


*Figure 6: LULC area percentage change from 2003-2023 for nine cities*

Here's the city wise detailed breakdown:

**Rajshahi, Bangladesh:** The urban area has increased from 15.06 km² to 28.89 km², which has increased by around 31% of the total land area. The vegetation area has decreased from 21.36 km² to 12.44 km², representing a 19.19% reduction in the total area. Water had no significant change from 0.89 km² to 0.98 km², and Bareland decreased by 10.74% - from 9.16 km² to 4.17 km².

**Chattogram, Bangladesh:** The urban area has increased by 16.50%, from 61.69 km² to 91.38 km². Vegetation has reduced by 9.06%, decreasing from 40.68 km² to 24.41 km². Bareland decreased by 8.19% from the total area, decreasing from 34.81 km² to 20.10 km², and water remained almost unchanged at around 62 km².

**Ahmedabad, India:** The urban area has expanded by 7.14%, increasing from 161.94 km² to 204.01 km². Vegetation has also surprisingly increased by 8.40%, from 31.11 km² to 80.18 km², which might be for the planned vegetation of the city authority during this 20-year period. Bareland has decreased by 16.04%, from 237.87 km² to 147.89 km². Water remained almost unchanged at around 6 km² to 7 km².

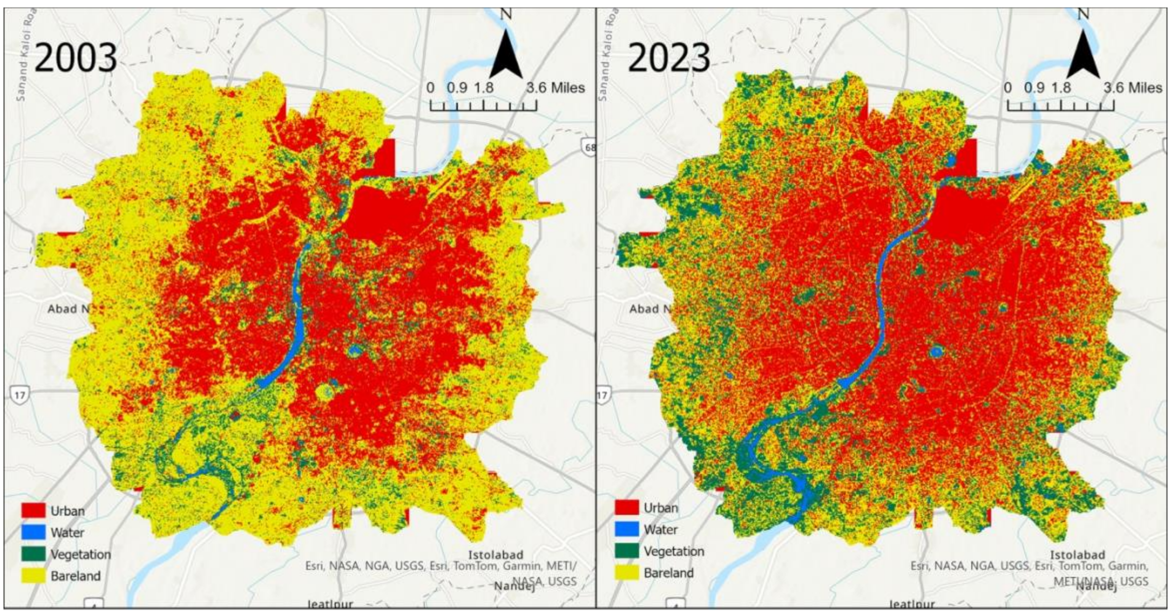


*Figure 7: LULC change of Ahmedabad Municipal Corporation from 2003-2023*

**Bhubaneswar, India:** There were huge urbanization in Bhubaneswar over 20-year. The urban area expanded significantly from 17.99 km² to 66.86 km², with a 32.52% increase based on the total city area. Vegetation decreased sharply (−22.61%), from 55.25 km² to 21.29 km². Bareland also declined, from 54.28 km² to 40.70 km² (−9.02%), while the waterbody area remained almost unchanged, from 22.75 km² to 21.41 km².

**Kanpur, India:** The urban area has a significant 26% expansion, increasing from 97.17 km² to 150.2 km². Vegetation decreased by 15%, from 93.76 km² to 52.4 km². Bareland has a slight decrease of 2.99%, from 65.41 to 57.27 km². The waterbody has decreased from 4.7 km² to 1.1 km².

**Gwadar, Pakistan:** The urban area has increased by 3.8%, from 124.5 km² to 168.5 km². The vegetated area has a slight increase from 72.5 km² to 82.7 km². Bareland decreased by 3.3%, from 972.9 km² to 937.76 km². Waterbody decreased by 1.46%, from 36.41 km² to 19.40 km².

**Quetta, Pakistan:** The urban area has increased by 5.83%, from 129.5 km² to 187.8 km² in the last 20 years. The vegetated area has a slight decrease by 1.76%, from 62.6 km² to 45.1 km². Waterbody percentage was insignificant for both years, from 0.03 km² in 2003 to 0.07 km² in 2023. Bareland has decreased by 4.08%, from 203.62 km² to 162.81 km².

**Kabul, Afghanistan:** The urban area has increased by 7.1% of the total area over 20 years, from 272.8 km² to 346.3 km². The vegetated area increased by 1.5%, from 38.3 km² to 54.1 km². Bareland has decreased from 712.1 km² to 616.2 km², accounting for a 9.3% decrease from the total area. Waterbody area nearly doubled, from 7.95 km² to 14.56 km², marking a 0.64% increase of the total area.

**Kathmandu, Nepal:** The urban area has increased from 36.61 sq km to 41.07 sq km, representing an 11.04% increase in the total area. Vegetation has decreased from 6.11 sq km to 4.72 sq km, showing a decline of 2.81%. Water bodies have slightly decreased by 0.95%, from 1.02 sq km to 0.55 sq km. Bareland has decreased by 7.28%, from 6.72 sq km to 3.12 sq km over 20 years.

The accuracy assessment have shown very good overall accuracy over all nine cities (≥0.96 except Chattogram) along with strong Kappa Coefficient values (Table-3) for both year 2003 and 2023, validating the good overall output of the machine learning model on google earth engine cloud platform.

| | | 2023 | | | | 2003 | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Country** | **City** | **Overall Accuracy** | **Overall Kappa Coefficient** | **Validation Accuracy** | **Validation Kappa Coefficient** | **Overall Accuracy** | **Overall Kappa Coefficient** | **Validation Accuracy** | **Validation Kappa Coefficient** |
| Bangladesh | Rajshahi | 0.96 | 0.94 | 0.76 | 0.63 | 0.98 | 0.97 | 0.64 | 0.41 |
| Bangladesh | Chittagong | 0.83 | 0.76 | 0.83 | 0.76 | 0.63 | 0.5 | 0.62 | 0.49 |
| India | Ahmedabad | 0.98 | 0.98 | 0.71 | 0.61 | 0.98 | 0.98 | 0.67 | 0.54 |
| India | Bhubaneswar | 0.98 | 0.98 | 0.72 | 0.62 | 0.98 | 0.98 | 0.57 | 0.42 |
| India | Kanpur | 0.98 | 0.98 | 0.75 | 0.64 | 0.97 | 0.96 | 0.69 | 0.54 |
| Pakistan | Gwadar | 0.98 | 0.97 | 0.67 | 0.49 | 0.97 | 0.96 | 0.48 | 0.25 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Pakistan | Quetta | 0.99 | 0.98 | 0.78 | 0.68 | 0.99 | 0.99 | 0.57 | 0.35 |
| Nepal | Kathmandu | 0.97 | 0.96 | 0.72 | 0.49 | 0.98 | 0.97 | 0.76 | 0.5 |
| Afghanistan | Kabul | 0.99 | 0.99 | 0.6 | 0.36 | 0.98 | 0.97 | 0.53 | 0.2 |

*Table 3: Accuracy Assessment of LULC Change Detection (2003-2023)*

Based on the 80/20 split, we also investigated the validation accuracy of the 20% test data of the training points. Validation accuracy also showed over 60–80% accuracy with moderate Kappa Coefficient values for the year 2003 and 2023 across nine cities.

### 3.2.2. LST Comparison of nine cities (2003 and 2023)

Landsat-based LST calculations have shown that mean annual temperature has increased in all nine cities. Mean annual LST for 2003 was 32.94°C; in 2023, the mean annual LST increased to 35.74°C, showing a 3.2°C increase in annual LST for the nine cities.

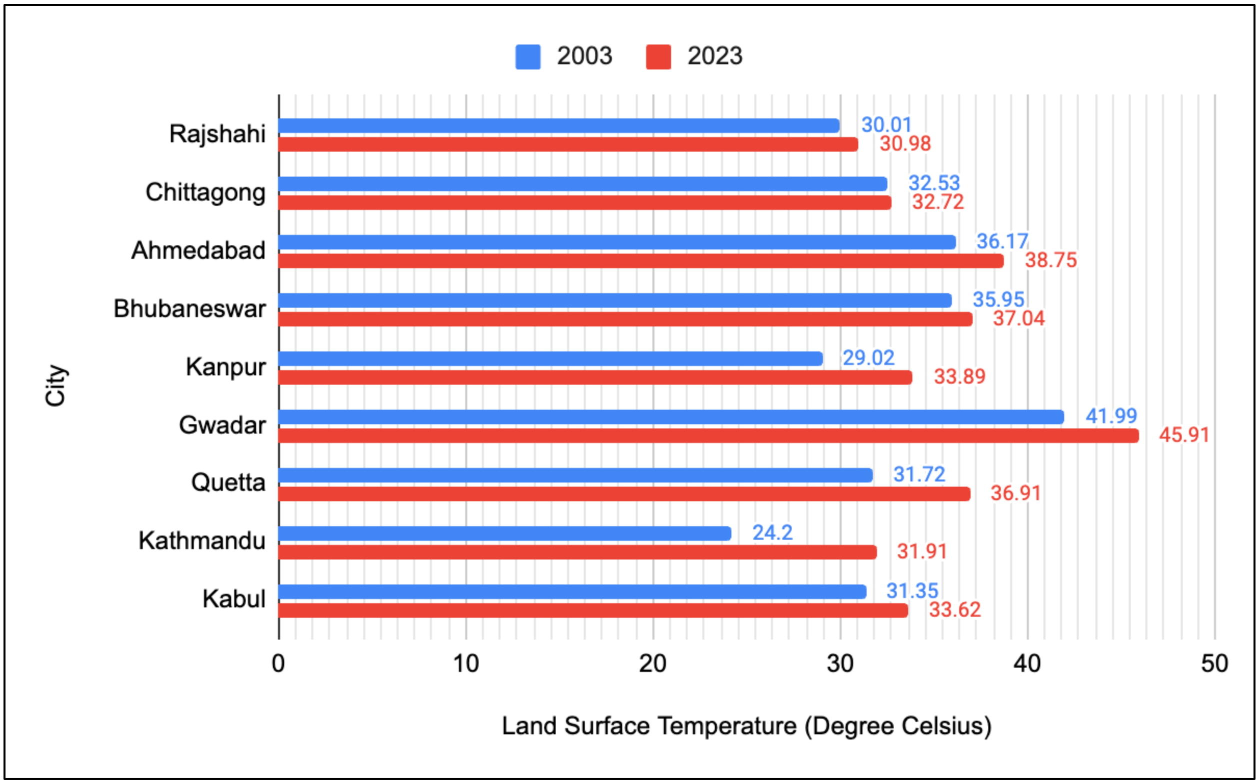


*Figure 8: LST Comparison of nine cities for the year 2003 and 2023*

Kathmandu in Nepal has shown the highest increase in annual mean LST, 7.71°C (Figure – 7). Quetta and Gwadar in Pakistan, and Kanpur in India have shown significant increases of 5.19°C, 3.92°C, and 4.87°C respectively. Ahmedabad in India and Kabul in Afghanistan have shown moderate increases with 2.58°C and 2.27°C respectively. Bhubaneswar in India and Rajshahi in Bangladesh had around a 1°C increase. Chittagong has shown the least increase, with 0.19°C.

### 3.2.3. Correlation Analysis Between Land Types

**LST vs. NDBI:** All of the cities have shown a positive correlation between LST and NDBI, indicating the contribution of built-up areas to increase the surface temperature and heat island effect. Kanpur has the highest positive correlation with the Pearson R coefficient value of 0.70, which indicates the strong warming impact of the built-up areas on the temperature. Ahmedabad, Bhubaneswar, and Chattogram have a strong positive correlation with the Pearson R coefficient values of 0.70, 0.63, 0.63, and 0.61, respectively. Kathmandu, Kabul, Rajshahi, Quetta, and Gwadar have a moderate positive correlation with the Pearson R coefficient value of 0.57, 0.53, 0.47, 0.43, and 0.41, respectively. All of the cities have a P value less than 0.001, which is statistically highly significant.

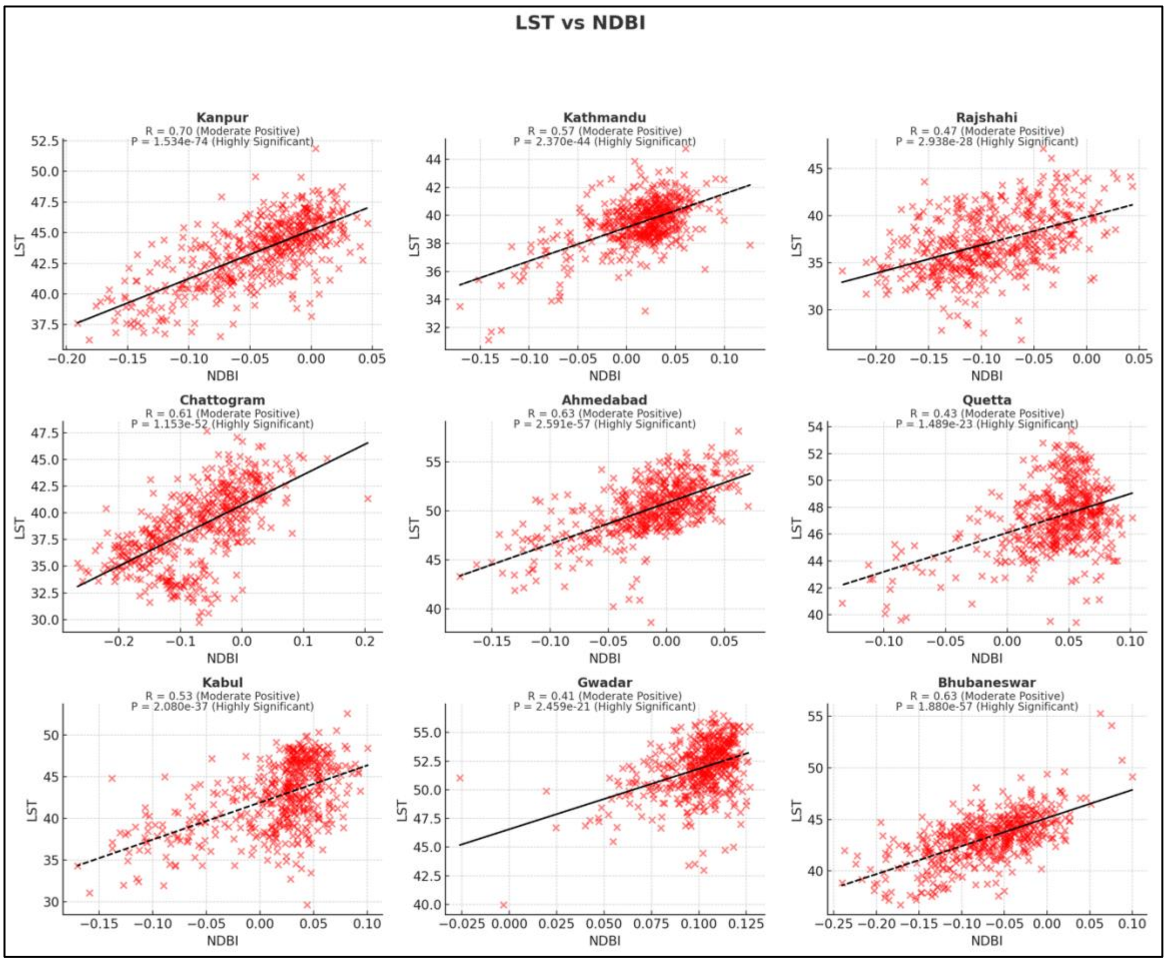


*Figure 9: Scatter Plot showing LST vs NDBI (Urban) values across nine cities*

**LST vs. NDVI:** All of the cities have shown a negative correlation between LST and NDVI, which indicates the more vegetation there is, the cooler the environment is. Kanpur has the highest negative correlation between LST and NDVI, with a Pearson correlation coefficient value of -0.66, meaning that vegetation has a high cooling impact in the city. Bhubaneswar, Kathmandu, and Kabul showed a negative correlation with Pearson R coefficient value of -.60, -.53, and -0.52, respectively. Rajshahi, Quetta, and Ahmedabad have shown a weak negative correlation with Pearson coefficient values of -0.39, -0.39, and -0.36, respectively. Chattogram and Gwadar, which are two coastal cities located in tropical and dry areas, have Pearson R coefficient values of -0.02 and -0.07, which is close to zero, indicating very little impact of vegetation on LST in these two cities.  Except for these two cities, all other cities have very low P values indicating strong statistical significance.

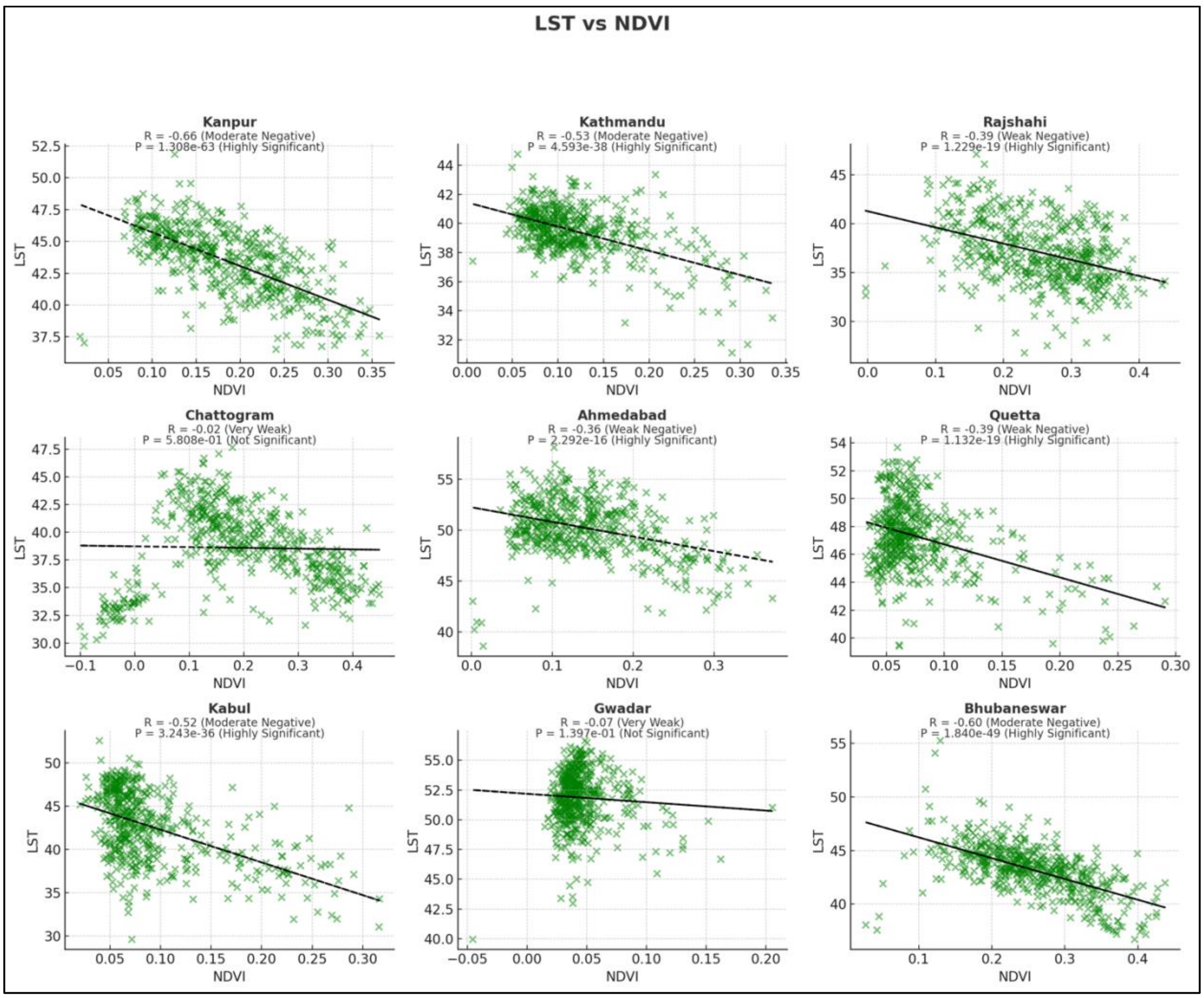


*Figure 10: Scatter Plot showing LST vs NDVI (Vegetation) values across nine cities*

**LST vs. MNDWI:** Except for Kathmandu and Kanpur, all the cities have shown a moderate to weak negative correlation of LST with the MNDWI, indicating a moderate, little, or no impact of water on the cooling effect of cities. Chattogram has the highest negative correlation of LST vs MNDWI with a Pearson R coefficient value of -0.53 amongst nine cities, which indicates a moderate cooling impact of water as it is a coastal city. Kabul, Quetta, Gwadar, and Ahmedabad have a weak negative correlation with a Pearson R coefficient value of -0.28, -0.26, -0.25, and -0.24 respectively, meaning that water has a cooling impact in these cities, but the effect is also not very strong. Bhubaneswar has a very weak negative correlation with a Pearson R coefficient value of -0.13. With a Pearson R coefficient value of -0.10, 0.01, and 0.07 which are close to zero, Rajshahi, Kathmandu, and Kanpur have almost no impact of water on the cooling effect in these cities, according to the Pearson R coefficient values. One thing to keep in mind is that this doesn't mean water has no cooling effect on the environment of these cities. Instead, it indicates that the percentage of water in these cities is very low compared to the total area, thus it cannot have a significant impact on temperature.

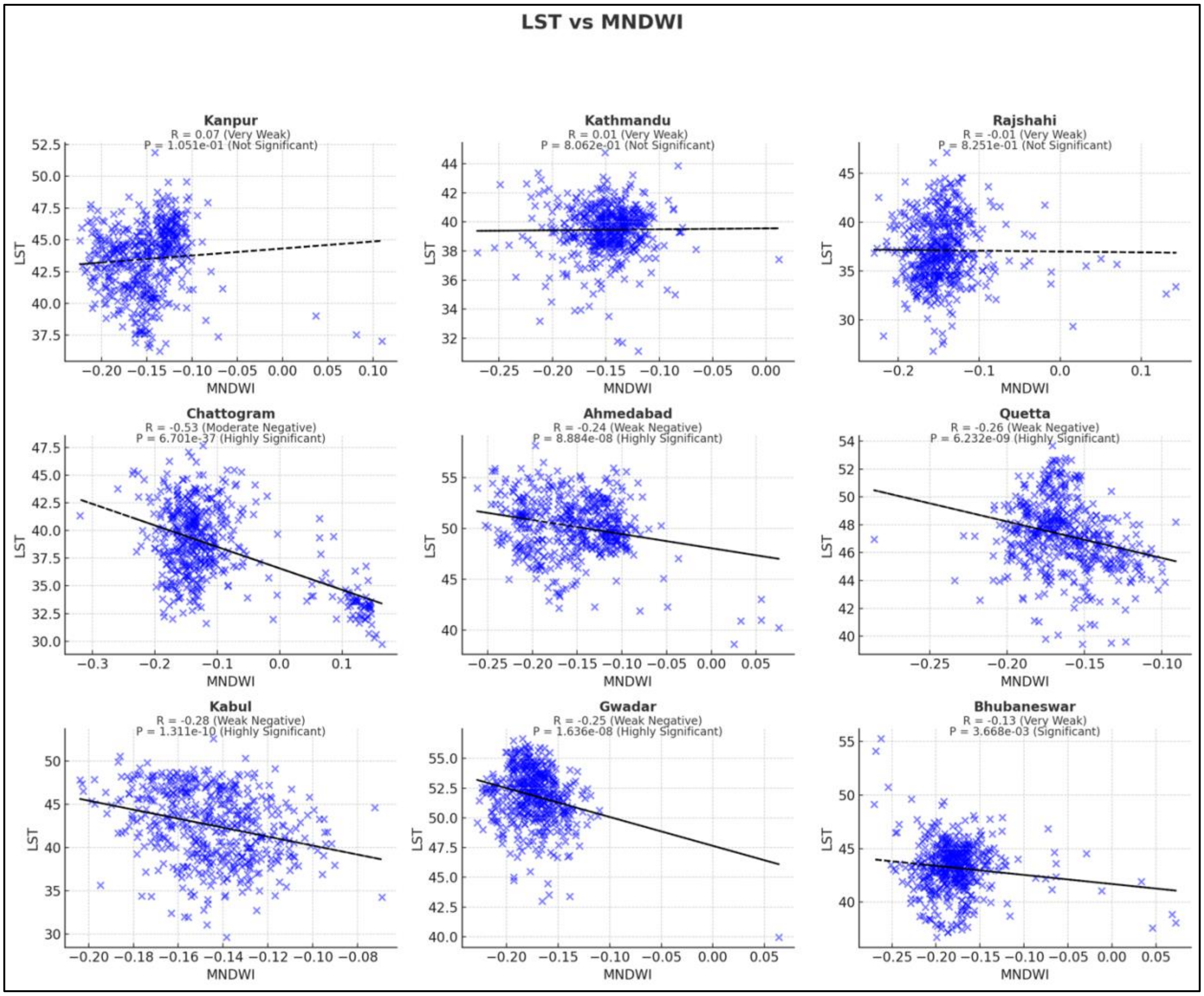


*Figure 11: Scatter Plot showing LST vs MNDWI (Water) values across nine cities*

### 3.3. Objective Two: Policy Review

**RQ:** How can HAPs be improved to reduce inequality in the context of increasing urban heat in South Asia?

**Objective:** To review the HAPs of two cities (Ahmedabad and Bhubaneswar) among the 9 cities to make them more spatially effective.

In South Asia, India has been the pioneer in formulating HAP at the city level, starting from Ahmedabad in 2013. Since then, numerous heat and climate action plans have been formulated in

India, Pakistan, Bangladesh, and other South Asian countries. Amongst the nine cities of the study locations, only Ahmedabad and Bhubaneswar have established city level HAPs. The National Disaster Management Authority (NDMA, 2017) in India has provided a national framework for preparing a HAP to prevent and manage the heatwaves. The World Health Organization (WHO/Europe, 2008) also suggested guidance on the Heat-Health Action Plan. Since our research question focuses on the heat equity of the vulnerable population, thematic content analysis was done for the two HAPs, keeping those national and international guidelines in mind to find the strengths and gaps to make these plans more people centered and spatially inclusive.

### 3.3.1. Ahmedabad HAP

This was the first ever city level HAP in South Asia published in 2013 for the implementation, coordination, and evaluation of heatwaves. Ahmedabad Municipal Corporation (AMC) started formulating it after the death of 1344 people during the devastating heatwave in 2010 (AMC, 2019). With the primary objective of alerting the population and taking precautions, this document has four key strategies: (1) public awareness building, (2) early warning system and interagency coordination, (3) capacity building among health professionals, and (4) reducing exposure and promoting adaptive measures. Under the AMC Nodal Officer, different departments like media, health, labor, etc. have specific roles. This document defines the heatwaves in AMC and describes the specific roles of these different departments for the pre, during, and post heatwave periods. It mentions immediate and short-term initiatives like early warning systems, training health professionals and local communities, preparing cooling centers, and the distribution of water. Midterm strategies like increasing green cover in specific areas, incorporating school volunteers, cool roof programs, etc. are geared towards the mitigation techniques of the heat risk. One study (Hess et al., 2018) suggests that 2380 deaths were avoided in the post HAP formulation period.


*Figure 12: Public Awareness Poster for Ahmedabad in Gujarat and English*

Though the AMC HAP is the pioneer as the first HAP in South Asia at the city level, this small document has some weaknesses considering the vulnerability mapping and identification of hotspots. Though it mentions workers, school children, disabled people, and other vulnerable populations that have a higher risk of heat related illness, it doesn't quite specify the hotspots or wards that are disproportionately more vulnerable than other neighborhoods. A fit-for-all approach might result in heat inequity, and not everyone can have access to the benefits from those initiatives.

### 3.3.2. Bhubaneswar HAP

Published in 2020, the Heatwave Action Plan for Bhubaneswar city was prepared by Integrated Research and Action for Development (IRADe) in collaboration with Bhubaneswar Municipal Corporation, Indian Institute of Public Health (IIPH)-Bhubaneswar, and Odisha State Disaster

Management Authority (OSDMA). It was an initiative to build a climate resilient city in the state of Odisha. The key strategies include establishing early warning systems, developing an interagency response plan, preparedness at the local level, capacity building of the health care system, public awareness, collaboration between stakeholders, and further assessment to update the plan.

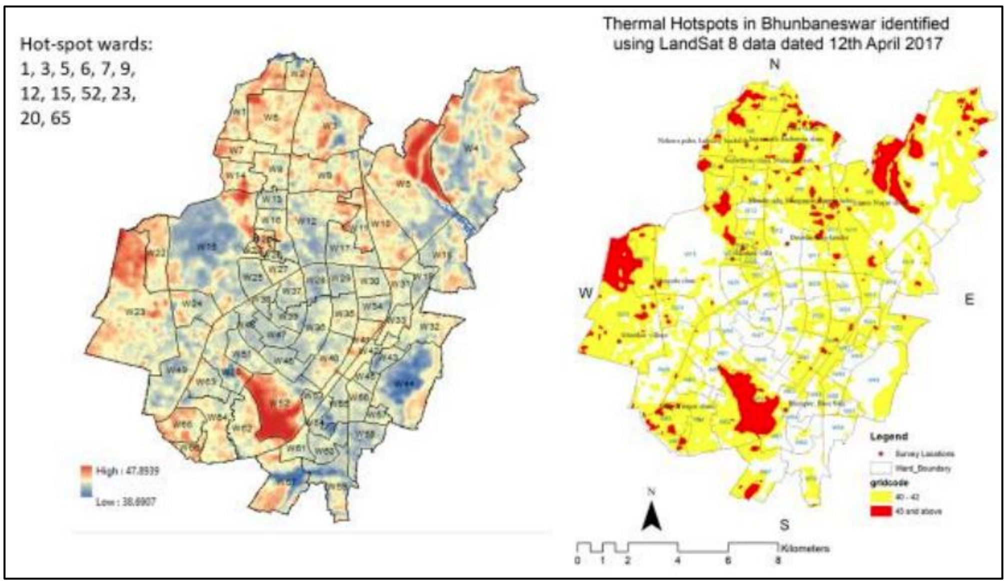


*Figure 13: Map Showing Thermal Hotspot in Bhubaneswar (derived from the report)*

The report does recognize the thermal hotspots and ward level vulnerability. A pre survey was conducted at 10 different hotspots, and vulnerability was assessed using a comprehensive index. Nine sectors were considered for indexing: sanitation, water, electricity, health, transportation, housing, cooking, awareness, and heat symptoms. The results found that four wards in Bhubaneswar were highly vulnerable where minimum amenities are available for the vulnerable population to adapt to heatwaves. The study identified the economic impact resulting from lost working hours and heat related health issues. Moreover, it identifies the gender specific impact of heat stress, indicating that women are more vulnerable to heat. Based on the study, the HAP has an emergency preparedness plan based on pre, during, and post heat season.

### 3.3.3. Comparison with International Guidelines

As a pioneer, Ahmedabad HAP was the first action plan developed to address heat stress on a city level in South Asia and paved the way for developing heat resilience for other cities. The HAP is a short document where the AMC collaborated with partners immediately after the deadly heatwave in 2010. The Bhubaneswar HAP was prepared by a research institute, Integrated Research and Action for Development (IRADe), in collaboration with other local and state level government agencies. Bhubaneswar's HAP is a well-documented policy framework drawing examples from previously established HAPs in India. The Ahmedabad HAP focused on short and mid-term actions, early warning systems, and preparedness plans. Several studies showed that it was effective in reducing mortality and other negative impacts (Hess et al., 2018). The Bhubaneswar HAP examined short and midterm measures like awareness, early warning communication, medical preparedness, etc., but also emphasized the need for long-term mitigation strategies to reduce the risk of the vulnerable population, like improving building structures, indigenous knowledge to develop protective measures, microclimatic research, urban greening through roof gardens, etc.

United Nations Office for Disaster Risk Reduction (2025) has suggested 13 points for making cities resilient, which also integrates suggestions from other guidelines. So, making this a guideline, here's the comparison of two cities about their HAP:

Here's a table comparing the HAPs of Ahmedabad and Bhubaneswar based on the 13 points from UNDRR:

| **Points** | **Ahmedabad** | **Bhubaneswar** |
|---|---|---|
| Conduct a City Baseline Heat Risk Assessment and Mapping | Not mentioned | Mentioned |
| Set Clear Heat-Planning Goals and Metrics | Mentioned | Mentioned |
| Develop a Comprehensive HAP and Integrate Heat Resilience in Long-Term Urban Planning | Not Mentioned | Mentioned |
| Ensure Cooling Solutions are Sustainable and Climate Friendly | Mentioned | Mentioned |
| Establish a Heat Alert System and Response Mechanism | Mentioned | Mentioned |
| Harness Political Leadership | Mentioned | Mentioned |
| Establish a Dedicated Focal Point for Heat Risk Management and Strengthen Coordination Across Essential City Systems | Mentioned | Mentioned |
| Build Awareness on Heat Risk Reduction at All Levels of Society | Mentioned | Mentioned |
| Engage All Relevant Stakeholders and Leverage Public Engagement | Mentioned | Mentioned |
| Strengthen Partnerships to Enhance Heat Risk Management | Mentioned | Mentioned |
| Leverage Public-Private Partnerships | Mentioned | Mentioned |
| Seek Diverse and Sustainable Financing for Heat Management | Not mentioned | Mentioned |
| Build Local Technical Capacities | Mentioned | Mentioned |

*Table 5: Comparison of two HAPs with UNDRR Guidelines*

Both of the strategies have their own pros and cons, but Bhubaneshwar HAP is more inclusive from our review – integrating risk reduction, identifying vulnerable groups, and developing long-term strategies to mitigate the risk for the future.

### 3.4. Objective Three: Heat Vulnerability Index

**RQ:** What is the spatial distribution of heat vulnerability in a South Asian city?

**Objective:** To develop a ward-wise HVI for Chattogram City in Bangladesh as a case study.

#### 3.4.1. HVI of Chattogram City Corporation

Thirteen variables were used to build the composite indicator of the Heat Vulnerability Index. It includes physical indicators: LST, NDVI, NDWI as well as social indicators: population density, female population, slum population, floating population, illiteracy rate, people and females involved in agriculture, percentage without internet access, poor housing, and lack of electricity. All of the variables were normalized using the min-max method, and the sum was calculated to build the index.

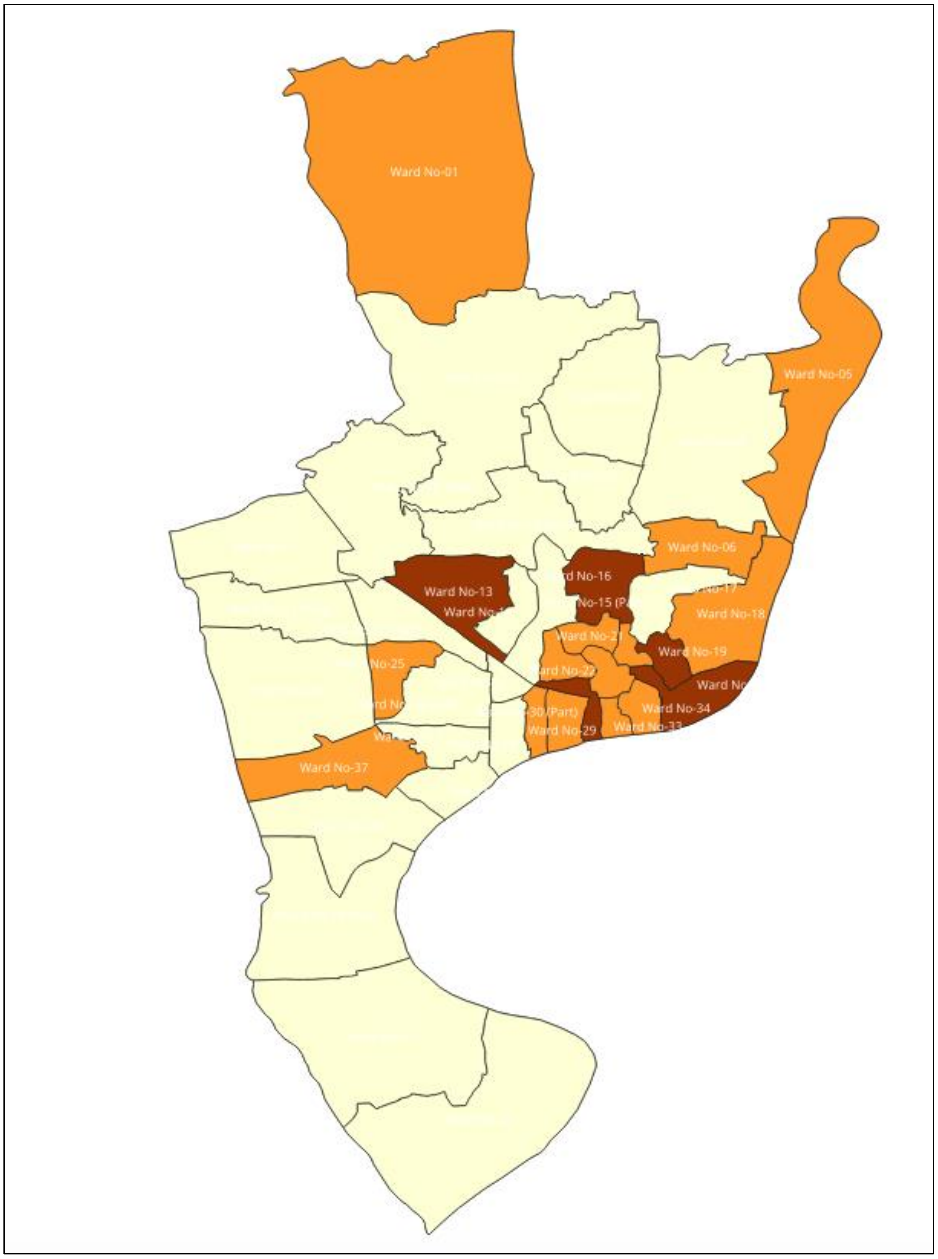


*Figure 14: Ward Level Heat Vulnerability Index of Chattogram City Corporation*

Results show that five wards, Ward Nos. 13, 16, 19, 30, and 35, were highly vulnerable to heat stress. Based on the weightage method provided on the GIS platform, these cities had higher population and higher LST with combination of other vulnerability factors. There are a total of 14 wards that have medium vulnerability: Ward Nos. 1, 5, 6, 18, 20, 21, 22, 25, 29, 31, 32, 33, 34, and 37.  The results show that 21 wards have low vulnerability.

### 3.5. Limitations

There were several limitations to this study. For the LULC change analysis, the number of points for each land type provided to the machine learning model can impact the results (Phinzi et al., 2023). Additionally, there was no ground-level verification of the LULC. The aim was to have an overall idea of the urbanization pattern and natural surface decrease in South Asian cities, but for one or two city-specific studies, more accuracy is needed. For the correlation analysis between land types and LST, there might be other factors contributing to LST, but this study analyzed the overall picture of urban, vegetation, and water.

For the HAP review, there was no field-level survey to investigate the impact of the post-HAP period. This study just reviewed the HAP documents found online and suggested recommendations based on those documents. It is possible that some initiatives which are implemented on the ground level are not mentioned in the policy document.

For the HVI, there were other variables that might be important for heat vulnerability, such as young and older people, pregnant women, outdoor workers, etc. However, finding data was a challenge since this study had to rely on available census information in South Asia. Ward-level data is difficult to find for all the variables in South Asia; sometimes governments conduct city-level surveys to get that data, which requires more resources.

## Chapter 4: Conclusion and Recommendations

Heatwaves are increasingly impacting the life and livelihood of South Asian cities. The increasing built-up area and reduced natural surfaces heavily contribute to the Urban Heat Island effect. Nine cities in five countries—Bangladesh (Rajshahi, Chattogram), India (Ahmedabad, Bhubaneswar, Kanpur), Pakistan (Gwadar, Quetta), Nepal (Kathmandu), and Afghanistan (Kabul)—were studied to examine the LULC change pattern and its impact on LST. Using satellite remote sensing and GIS techniques, this study clearly shows that all nine cities in South Asia have an increasing built-up area over a 20-year period, which is taking over natural surfaces like vegetation and water. The mean annual LST has increased in all of the cities, with some showing a high increase and others a moderate one. The correlation analysis indicates that despite microclimatic differences, geographic location (inland or coastal), or landform (wet or dry), the built-up area has the highest influence on LST. Vegetation has a medium cooling impact in cities, and water bodies contribute very little to the cooling effect because of the very limited presence of water in these cities. Governments need to prioritize strategies for long-term land use planning to reduce heat vulnerability in the cities.

HAPs are effective in saving lives and reducing economic impact. As temperatures continue to rise, the need for HAPs is very important—not only at the national level climate policy but also at the city level HAPs or comprehensive climate action plans that consider heat as a major threat. The reviewed HAPs of Ahmedabad and Bhubaneswar show how planning can be improved by integrating vulnerability and risk mapping, including the use of geospatial technologies in policy planning. The key idea is to understand the heat risk first and then plan accordingly. GIS and remote sensing techniques can be very useful in this regard. This is why a HVI for Chattogram City Corporation was constructed, showing how vulnerable populations are more concentrated in the mid-eastern part of the city. Physical parameters and social indicators were merged to build the HVI. One of the primary challenges in developing the HVI was the lack of available data. This highlights a critical area where South Asian national and local governments need to invest more effort—by conducting comprehensive surveys and ensuring that relevant datasets are made publicly available for researchers and policymakers.

Overall, planning for short and mid-term HAPs and coordinating with long-term land use policies of the cities can help fight heat risk and reduce people's vulnerability in South Asia. Different stakeholders – national and local governments, researchers, and private institutions need to collaborate to enhance the effectiveness of climate and heat-related policies and to build resilient cities.

## References


1. Abadie, A., Athey, S., Imbens, G., & Wooldridge, J. (2020). Sampling-based vs. design-based uncertainty in regression analysis. *Econometrica, 88*(1), 265-296.
2. Arnfield, A. J. (2003). Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology, 23*(1), 1-26.
3. Basu, R., & Samet, J. M. (2002). Relation between elevated ambient temperature and mortality: A review of the epidemiologic evidence. *Epidemiologic Reviews, 24*(2), 190-202.
4. Brown, R. D., & Gillespie, T. J. (1995). Microclimatic landscape design: Creating thermal comfort and energy efficiency. Wiley.
5. Cheng, X., Wei, B., Chen, G., Li, J., & Song, C. (2018). Influence of park size and its surrounding urban morphology on the cooling effect of urban green spaces: A case study in Beijing, China. *Urban Forestry & Urban Greening, 31*, 120-128.
6. Chow, W. T. L., & Roth, M. (2006). Temporal dynamics of the urban heat island of Singapore. *International Journal of Climatology, 26*(15), 2243-2260.
7. Debbage, N., & Shepherd, J. M. (2015). The urban heat island effect and city contiguity. *Computers, Environment and Urban Systems, 54*, 181-194.
8. Dixon, P. G., & Mote, T. L. (2003). Patterns and causes of Atlanta's urban heat island–initiated precipitation. *Journal of Applied Meteorology, 42*(9), 1273-1284.
9. Erell, E., Pearlmutter, D., Boneh, D., & David, M. (2014). Urban microclimate modeling for pedestrian thermal comfort: Current uses and future possibilities. *Building and Environment, 73*, 81-91.
10. Gago, E. J., Roldan, J., Pacheco-Torres, R., & Ordóñez, J. (2013). The city and urban heat islands: A review of strategies to mitigate adverse effects. *Renewable and Sustainable Energy Reviews, 25*, 749-758.
11. Grimmond, C. S. B., & Oke, T. R. (1999). Aerodynamic properties of urban areas derived from analysis of surface form. *Journal of Applied Meteorology, 38*(9), 1262-1292.
12. Gunderson, L. H., & Holling, C. S. (2002). *Panarchy: Understanding transformations in human and natural systems*. Island Press.
13. Gupta, K., Kumar, P., Pathan, S. K., & Sharma, K. P. (2012). Urban neighborhood green index–A measure of green spaces in urban areas. *Landscape and Urban Planning, 105*(3), 325-335.
14. Harlan, S. L., & Ruddell, D. M. (2011). Climate change and health in cities: Impacts of heat and air pollution and potential co-benefits from mitigation and adaptation. *Current Opinion in Environmental Sustainability, 3*(3), 126-134.
15. Howard, L. (1833). *The climate of London* (Vol. 1). Harvey and Darton.
16. Imhoff, M. L., Zhang, P., Wolfe, R. E., & Bounoua, L. (2010). Remote sensing of the urban heat island effect across biomes in the continental USA. *Remote Sensing of Environment, 114*(3), 504-513.
17. IPCC. (2021). Climate change 2021: The physical science basis. *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.

18. Jenerette, G. D., Harlan, S. L., Stefanov, W. L., & Martin, C. A. (2011). Ecosystem services and urban heat riskscape moderation: Water, green spaces, and social inequality in Phoenix, USA. *Ecological Applications, 21*(7), 2637-2651.
19. Jesdale, B. M., Morello-Frosch, R., & Cushing, L. (2013). The racial/ethnic distribution of heat risk–related land cover in relation to residential segregation. *Environmental Health Perspectives, 121*(7), 811-817.
20. Kintisch, E. (2016). *Hack the planet: Science's best hope—or worst nightmare—for averting climate catastrophe*. Wiley.
21. Kleerekoper, L., Van Esch, M., & Salcedo, T. B. (2012). How to make a city climate-proof, addressing the urban heat island effect. *Resources, Conservation and Recycling, 64*, 30-38.
22. Li, X., Zhou, W., & Ouyang, Z. (2013). Relationship between land surface temperature and spatial pattern of greenspace: What are the effects of spatial resolution? *Landscape and Urban Planning, 114*, 1-8.
23. Luber, G., & McGeehin, M. (2008). Climate change and extreme heat events. *American Journal of Preventive Medicine, 35*(5), 429-435.
24. McGregor, G. R., & Vanos, J. K. (2018). Heat: A primer for public health researchers. *Public Health, 161*, 138-146.
25. Middel, A., Häb, K., Brazel, A. J., Martin, C. A., & Guhathakurta, S. (2014). Impact of urban form and design on mid-afternoon microclimate in Phoenix Local Climate Zones. *Landscape and Urban Planning, 122*, 16-28.
26. Mills, G. (2006). Progress toward sustainable settlements: A role for urban climatology. *Theoretical and Applied Climatology, 84*(1-3), 69-76.
27. Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society, 108*(455), 1-24.
28. Oke, T. R. (1987). *Boundary layer climates* (2nd ed.). Routledge.
29. Rinner, C., & Hussain, M. (2011). Toronto's urban heat island—Exploring the relationship between land use and surface temperature. *Remote Sensing, 3*(6), 1251-1265.
30. Roth, M. (2007). Review of urban climate research in (sub)tropical regions. *International Journal of Climatology, 27*(14), 1859-1873.
31. Santamouris, M. (2013). Using cool pavements as a mitigation strategy to fight urban heat island—A review of the actual developments. *Renewable and Sustainable Energy Reviews, 26*, 224-240.
32. Santamouris, M. (2015). Analyzing the heat island magnitude and characteristics in one hundred Asian and Australian cities and regions. *Science of the Total Environment, 512-513*, 582-598.
33. Santamouris, M., Cartalis, C., Synnefa, A., & Kolokotsa, D. (2015). On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings—A review. *Energy and Buildings, 98*, 119-124.
34. Smith, C., & Levermore, G. (2008). Designing urban spaces and buildings to improve sustainability and quality of life in a warmer world. *Energy Policy, 36*(12), 4558-4562.
35. Stone, B., Hess, J. J., & Frumkin, H. (2010). Urban form and extreme heat events: Are sprawling cities more vulnerable to climate change than compact cities? *Environmental Health Perspectives, 118*(10), 1425-1428.

36. Stott, P. A., Stone, D. A., & Allen, M. R. (2004). Human contribution to the European heatwave of 2003. *Nature, 432*(7017), 610-614.
37. Tan, J., Zheng, Y., Tang, X., Guo, C., Li, L., Song, G., ... & Chen, H. (2010). The urban heat island and its impact on heat waves and human health in Shanghai. *International Journal of Biometeorology, 54*(1), 75-84.
38. Van Hove, L. W. A., Jacobs, C. M. J., Heusinkveld, B. G., Elbers, J. A., van Driel, B. L., & Holtslag, A. A. M. (2015). Temporal and spatial variability of urban heat island and thermal comfort within the Rotterdam agglomeration. *Building and Environment, 83*, 91-103.
39. Voogt, J. A., & Oke, T. R. (2003). Thermal remote sensing of urban climates. *Remote Sensing of Environment, 86*(3), 370-384.
40. Weng, Q., Liu, H., & Lu, D. (2007). Assessing the effects of land use and land cover patterns on thermal conditions using landscape metrics in city clusters. *International Journal of Remote Sensing, 28*(10), 2125-2138.
41. Wheeler, S. M. (2013). Planning for urban resilience in the era of climate change. In S. Davoudi, J. Crawford, & A. Mehmood (Eds.), *Planning for Climate Change: Strategies for Mitigation and Adaptation for Spatial Planners* (pp. 149-158). Routledge.
42. Wilby, R. L. (2007). A review of climate change impacts on the built environment. *Built Environment, 33*(1), 31-45.
43. World Health Organization. (2018). *COP24 special report: Health and climate change*. WHO.
44. Xu, Y., Shen, Y., Tam, V. W. Y., & Ji, Y. (2019). Impact of urbanization on spatiotemporal variations in land surface temperature in large cities of China. *Remote Sensing, 11*(6), 665.
45. Yang, X., & Meng, F. (2014). Understanding the spatial variability of urban heat islands by local climate zones. *Remote Sensing Letters, 5*(4), 315-323.
46. Zhang, Q., & Seto, K. C. (2011). Mapping urbanization dynamics at regional and global scales using multi-temporal DMSP/OLS nighttime light data. *Remote Sensing of Environment, 115*(9), 2320-2329.
47. Zhou, D., Zhao, S., Liu, S., Zhang, L., & Zhu, C. (2014). Surface urban heat island in China's 32 major cities: Spatial patterns and drivers. *Remote Sensing of Environment, 152*, 51-61.
48. Nair, U. S., Phillips, C., Dasgupta, S., & Mitra, C. (2023). Impact of growth of a medium-sized Indian coastal city on urban climate: A case study using data fusion and analytics. *Urban Climate*, *49*, 101525.
49. Shrestha, M., Mitra, C., Rahman, M., & Marzen, L. (2022). Mapping and predicting land cover changes of small and medium size cities in Alabama using machine learning techniques. *Remote Sensing*, *15*(1), 106.
50. Santamouris, M., Cartalis, C., Synnefa, A., & Kolokotsa, D. (2015). On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings—A review. *Energy and buildings*, *98*, 119-124.
51. NDMA (2019). National Guidelines for preparation of Action Plan- Prevention and management of heat wave. https://nidm.gov.in/PDF/pubs/NDMA/27.pdf

52. AMC (2019), Ahmedabad Heat Action Plan. https://www.nrdc.org/sites/default/files/ahmedabad-heat-action-plan-2019-update.pdf
53. WHO/Europe (2008), Heat-Health Action Plan Guidance. https://ghhin.org/wp-content/uploads/E91347.pdf
54. Sharma, A., Andhikaputra, G., & Wang, Y.-C. (2022). Heatwaves in South Asia: Characterization, consequences on human health, and adaptation strategies. *Atmosphere, 13*(5), 734. https://doi.org/10.3390/atmos13050734
55. Debnath, K. B., Jenkins, D. P., Patidar, S., Peacock, A. D., & Bridgens, B. (2023). Climate change, extreme heat, and South Asian megacities: Impact of heat stress on inhabitants and their productivity. *Journal of Engineering for Sustainable Buildings and Cities, 4*(4), 041006. https://doi.org/10.1115/1.4064021
56. Rana, I. A., Sikander, L., Khalid, Z., Nawaz, A., Najam, F. A., Khan, S. U., & Aslam, A. (2022). A localized index-based approach to assess heatwave vulnerability and climate change adaptation strategies: A case study of formal and informal settlements of Lahore, Pakistan. *Environmental Impact Assessment Review, 96*, 106820. https://doi.org/10.1016/j.eiar.2022.106820
57. Singh, A. M. (2023). Mapping of heat vulnerability in Indian urban centres under threat of global warming. *Journal of Applied and Natural Science, 15*(4), 1514-1519. https://doi.org/10.31018/jans.v15i4.5039
58. Azhar, G., Saha, S., Ganguly, P., Mavalankar, D., & Madrigano, J. (2017). Heat wave vulnerability mapping for India. *International Journal of Environmental Research and Public Health, 14*(4), 357. https://doi.org/10.3390/ijerph14040357
59. World Health Organization. (2008). *Heat-health action plans: guidance*. WHO Regional Office for Europe. Retrieved from https://www.who.int/publications/i/item/9789289071918
60. United Nations Office for Disaster Risk Reduction. (2025). *Urban Extreme Heat Risk Management - Resource Package*. UNDRR. Retrieved from https://www.undrr.org/publication/urban-heat-risk-management-resource-package
61. Hussainzad, E. A., & Gou, Z. (2024). Climate risk and vulnerability assessment in informal settlements of the Global South: A critical review. *Land, 13*(9), 1357. https://doi.org/10.3390/land13091357
62. United Nations Economic and Social Commission for Asia and the Pacific (UN ESCAP). (2025). *Asia's megacities at a crossroads as climate and population challenges grow*. UN News. https://news.un.org/en/story/2025/04/1162451
63. Islam, S., Karipot, A., Bhawar, R., Sinha, P., Kedia, S., & Khare, M. (2024). Urban heat island effect in India: A review of current status, impact and mitigation strategies. *Discover Cities, 1*(34). https://doi.org/10.1007/s44327-024-00033-3

64. Uddin, M. N., Rahman, M. M., & Islam, M. T. (2021). Changes in urbanization and urban heat island effect in Dhaka city. *Theoretical and Applied Climatology, 145*, 123–138. https://doi.org/10.1007/s00704-021-03872-x

65. Khan, N., & Shahid, S. (2024). Urban heat island effect and its drivers in large cities of Pakistan. *Theoretical and Applied Climatology, 155*, 5433 5452. https://doi.org/10.1007/s00704-024-04959-x
66. Komaroff, E. (2020). Relationships between p-values and Pearson correlation coefficients, type 1 errors and effect size errors, under a true null hypothesis. *Journal of Statistical Theory and Practice, 14*(49). https://doi.org/10.1007/s42519-020-00115-6
67. Wubante, M. (2020). Review on correlation research. *International Journal of English Literature and Culture, 8*(4), 99–106. https://www.academicresearchjournals.org/IJELC/PDF/2020/July/Wubante.pdf
68. Ahmedabad Municipal Corporation. (2023). *Ahmedabad Climate Resilient City Action Plan – Towards a Net Zero Future*. ICLEI South Asia. https://www.cities-and-regions.org/wp-content/uploads/2023-ahmedabad-climate-resilient-city-action-plan-compressed.pdf
69. Phinzi, K., Odindi, J., & Mutanga, O. (2023). Understanding the role of training sample size in the uncertainty of high-resolution LULC mapping using random forest. *Earth Science Informatics*. https://doi.org/10.1007/s12145-023-01117-1