URBAN HEAT ISLAND (UHI) DEVELOPMENT AND MITIGATION MEASURES IN THREE BANGLADESH CITIES: DHAKA, CHATTOGRAM, AND SYLHET

by

Israt Jahan

A dissertation submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Geography

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ABSTRACT

The surge in urban population worldwide has led to a swift expansion of urban areas and noticeable temperature differences between urban centers and their rural surroundings. This phenomenon, known as the Urban Heat Island (UHI) effect, is increasingly recognized as a significant human impact on the environment with both local and global consequences. The rapidly expanding populations in Asian cities, including Bangladesh cities, are anticipated to be highly susceptible to these impacts. Although the UHI effect has been extensively studied in both large and medium-sized cities globally, comparative research on rapidly developing Bangladesh cities remains sparse. The study compares the UHI development in the three largest cities of Bangladesh that includes Dhaka, Chattogram (previously known as Chittagong), and Sylhet, after documenting the changes in land use patterns in the current municipal boundary and proposed future extension areas over the last two decades. The research also integrates uncertainty maps to specify the confidence levels in land use classification results that are not prevalent in prior studies. Additionally, most existing studies have relied solely on satellite data to analyze the land surface temperature (LST) to quantify the surface urban heat island (SUHI), often overlooking the atmospheric urban heat island (AUHI). This study combines in-situ measurements (AUHI) with remotely sensed data (SUHI) to assess the spatiotemporal variability of the city's microclimate. The dew point temperature was computed in conjunction with temperature to enhance the understanding of heat stress conditions. Along with evaluating the temperature and dew points trends over the twenty year period, their

statistical significance was computed using the Mann-Kendall test and the *t*-test performed to determine if the urban and rural time series were distinct. The final step of this study investigated the UHI mitigation measures addressed in each city's future development plans to reduce urban warming effects by increasing green spaces (such as parks, rooftop gardens, and vertical green walls) and blue spaces (such as rivers, ponds, and lakes). Effective mitigation strategies most appropriate for each city's urban context were highlighted to help urban planners and policymakers take immediate action to reduce the adverse impacts of UHI and ensure sustainable and livable urban environments.

Chapter 1

INTRODUCTION

Urban Heat Island (UHI) is a meteorological phenomenon where urban areas experience significantly higher temperatures than their rural surroundings. This temperature difference is primarily due to human activities and the alteration of natural landscapes, including the extensive use of concrete, asphalt, and buildings that absorb and retain heat. UHI can intensify energy consumption, elevate air pollution levels, and negatively impact human health. UHI is not just an abstract meteorological phenomenon; it's a pressing crisis affecting cities globally, with the UHI challenges increasing as cities continue to grow. A projection by the United Nations (UN) shows that 68% of the world's population will reside in urban areas by 2050, with 90% of this urban growth occurring in low- and middle-income countries in Asia and Africa (United Nations, 2018). Bangladesh, a south Asian developing country, is no exception.

Bangladesh is one of the most populated developing countries in the world (population density 1,119 people per km^2; BBS, 2022). Due to its rapid, unplanned urbanization (31.5% of people live in urban areas in 2021; BBS, 2022), Bangladesh is experiencing the adverse impact of UHI. The growing population density in Bangladesh's cities is reducing surface water bodies and vegetation as urban areas expand, leading to an accelerated increase in land surface temperature (LST) (Yin et al., 2018). The major cities of Bangladesh already have elevated temperatures in comparison to its surrounding rural areas. Here, immediate action to understand and

mitigate UHI effects is essential - not just for sustainable urban development but also for safeguarding the future of the cities and improving the quality of life for millions of people in densely populated areas.

This research investigates the UHI scenario in three large cities in Bangladesh: Dhaka, Chattogram (previously called ‘Chittagong’), and Sylhet. These cities are of significant socio-economic importance and vary in population density and growth rate, land use patterns, topography, and weather. Dhaka is the capital of Bangladesh and one of the fastest-growing megacities in the world, occupying more than ten million people (10,278,882) in 2022 (BBS, 2022). Chattogram is the port city and the second largest city in Bangladesh, experiencing rapid urbanization over the last few decades, with a city population of 3,227,246 in 2022 (BBS, 2022). Sylhet, with a population of 532,426 in 2022 (BBS, 2022), is also a fast-growing urban area.

To address the UHI in these three large cities of Bangladesh, this research first investigates the change in land use, as urbanization is the main factor of UHI development in a city (Floreano & de Moraes, 2021). Urbanization transforms land use (Kotharkar et al., 2019), offering social and economic benefits to people while simultaneously posing environmental challenges (Estoque & Murayama, 2014). The rapid growth of urbanization has caused the gradual destruction of forests, water bodies and vegetation in cities (Liu et al., 2015). Urbanization continuously replaces natural land cover with artificial surfaces that alter the land surface's thermal properties, energy flow, and air circulation characteristics, leading to a gradual increase in heat storage, surface temperature, and deteriorating the urban environment (Huang, 2011; Liu et al., 2019). To document the UHI situation in the three Bangladesh metropolitan areas, both atmospheric urban heat island (AUHI) and

surface urban heat island (SUHI) were evaluated. AUHI indicates the differences in air temperatures between urban and rural areas, and SUHI measures the change in land surface temperatures (LST) for the different land use types.

After documenting the UHI impact in the study areas, the research examined the development plans of each Bangladesh city and reviewed other UHI mitigation studies globally to curb the effect of the UHI. The study concludes with policy recommendations for Bangladesh to mitigate the UHI impacts.

The research is divided into three chapters with the following objectives:

(a) to document the overall land use changes in Dhaka, Chattogram, and Sylhet over the last two decades and quantify the rate of urbanization between the three cities from 2001 to 2021,

(b) to identify the AUHI (over 35 years) and SUHI (20 years) intensity in the three cities and the significant differences, and

(c) to evaluate the UHI mitigation measures addressed in the existing municipal development plans and offer suggestions for improvements from other global studies.

Each of these objectives is addressed in separate chapters of the dissertation. Chapter 2 compares the land use change patterns in the study cities. The land surfaces of these three cities within the current municipal boundaries and their surrounding periphery buffer area (designated by the municipal authority as the future city expansion zone) were classified into five land use types (built-up, agriculture, forest, waterbody, and barren) using Landsat 5 and Landsat 8 satellite data (with a spatial resolution of 30m) on the Google Earth Engine (GEE) cloud computing platform, employing a time-composited image stack (4 time-periods over 3 years) that consisted

of 44 bands. The overall accuracies were evaluated by computing error matrices and mapping the multiprobability of each land use class as uncertainty maps. Such maps, derived using Google Earth Engine's multiprobability feature, provide the probabilities associated with each land use class. Chapter 3 examines the AUHI and SUHI intensities in Bangladesh cities. AUHI intensities were assessed using observed air temperature data collected from urban and rural weather stations since 1988. Pairing relative humidity information with the temperature analysis was also performed to help understand the extent of heat stress, especially in environments where high temperatures and humidity combine to create potentially hazardous conditions as they do in tropical environments like Bangladesh. Alongside examining the AUHI, SUHI intensities were evaluated by comparing the land surface temperature (LST) of impervious built-up areas to that of permeable non-built-up areas, using MODIS and Landsat satellite imagery data since 2001. Landsat provides daytime and MODIS provides both day and nighttime information. Chapter 4 evaluates the existing development plans prepared by the Bangladesh municipal authorities that are intended to direct the cities' future development with a lens related to the mitigation of UHI impacts. This chapter also examines possible mitigation techniques recommended in the literature that would be appropriate and beneficial for Bangladesh cities. Finally, Chapter 5 integrates the conclusions from the previous chapters to address the overarching research goal of this dissertation to address the UHI situation in the three largest Bangladesh cities and provide suggestions for effective mitigation strategies. In summary this study contributes significantly to provide a complete understanding of the UHI situation in the three Bangladesh cities, starting from the land use change as a

driver of UHI development, documenting the present UHI in the study areas, and emphasizing effective strategies to mitigate the adverse effects of UHI.

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Chapter 2

URBAN GROWTH AND LANDSCAPE CHANGE IN THREE BANGLADESH CITIES: DHAKA, CHATTOGRAM, AND SYLHET

2.1 Introduction

Less than one-third of the world's population (751 million) dwelled in cities in 1950 (United Nations Population Fund, 2007), and today more than half (55%) of the population (4.2 billion) live in urban areas (United Nations, 2018). The United Nations (UN) projects the urban population to reach 68% of the global population by 2050, with 90% of the urban population growth to occur in low- and middle-income countries of Asia and Africa (United Nations, 2018). As people continue to move into urban areas and their spatial footprint continues to grow, it is crucial to understand the pattern and intensity of urbanization processes and the resulting impact of land use change has on natural resource use, human health, and global environmental change (Seto & Reenberg, 2014). This information will contribute to understanding of urban growth and support planning for a sustainable urban future, aligning with the vision outlined in the United Nations Sustainable Development Goal 11 (Sustainable Cities and Communities) (United Nations n.d.).

Urbanization can be monitored over time by observing the land use change from natural landscapes to built-up areas (Acheampong, 2019). Many studies of such land use conversions have used remote sensing and geographic information system (GIS) technologies relying on satellite imagery at various levels of spatial resolution. These studies have examined land use changes over large and small geographic areas

covering urbanizing areas in the United States, Europe, and several Asian cities (Chamling & Bera, 2020; Ding &Shi, 2013; Dissanayake et al., 2019; Giri et al., 2003; Homer et al., 2020; Hu et al., 2019; Jin et al., 2019; Mansour, Al-Belushi, & Al-Awadhi, 2020; Singh et al., 2021; Vadrevu, 2018; Vadrevu et al., 2019; Verma & Raghubanshi, 2019; Ullah et al., 2019). Even with the few studies concentrating on Asian cities, Vadrevu (2018) argues that land use changes in Asian cities are poorly understood and need more detailed and immediate attention as this region accounts for 35% of the total population from less than 2% of the world's area with the highest population growth rate. Population growth and urbanization will continue to exert enormous pressures by converting land from natural and agricultural areas to residential and urban uses with significant impacts (Vadrevu, 2018). A key strategy is to balance land use change that provides pathways for improved standards of living while minimizing the negative human health and environmental impacts. To be able to address this key issue, documenting the land use changes are critical.

This study focuses on the country of Bangladesh, which is experiencing rapid and unplanned urbanization. As mainly an agrarian country before its independence in 1971, the urban area population has increased more than fourfold since the country achieved independence (United Nations, 2018). Only 8% of the Bangladesh population was urban in 1972, and today, approximately 37% of people reside in urban areas with a projected rise to 58% by 2050 (United Nations, 2018). The urban population is highly concentrated in limited land areas, resulting in substandard living conditions that threaten human health and create environmental degradation (Vadrevu, 2018). Although the environmental impacts of urban areas are indisputable, cities hold a special place as the cultural, business, education, innovation, entertainment, and

political heart of a nation. Bangladesh is no exception, with 64% of the national gross domestic product generated in the urban areas (Hassan, 2017; UPPR, 2011). Urbanization is an essential phenomenon in the country's economic development, social progress, and cultural transformation (Hassan, 2017). People migrate to cities to ensure better living standards, employment, housing, education, health care, and lifestyle (Tiwari & Kulshrestha, 2018; Winters, 2011). Therefore, urban growth and its changing patterns must be monitored and characterized carefully to understand its impacts on the environment and provide guidance to local authorities and policymakers to manage and utilize limited land-based resources properly and develop strategies for sustainable urban development. The emphasis on Bangladesh is relevant to other megacities in southeast Asia and the Global South, such as China, Vietnam, India, Indonesia, etc., that are experiencing the same social, economic, and environmental challenges of urban growth and a sustainable future for its people.

Our study provides a comparative analysis of Bangladesh's three largest cities, Dhaka, Chattogram (previously called 'Chittagong'), and Sylhet, to document the land use changes over the past 20 years within the current administrative city boundaries and the growth that has taken place in the cities' administrative future expansion boundaries determined by the municipal authority. All three cities' geographic areas have been growing historically to accommodate the increased urban population, with the municipal authorities continuing to extend their jurisdiction boundary to disperse the high-density urban population. The future expansion areas of cities represent an additional dimension that has not been examined in previous studies, offering insights into how urban development is extending and accelerating within these planned administrative boundaries. This land use study has two research objectives, including

(a) documenting the overall land use change in Dhaka, Chattogram, and Sylhet over the last two decades and (b) quantifying the rate of urbanization between the three cities from 2001 to 2021. The study is a necessary precursor to investigating environmental issues such as urban heat islands by providing a foundational analysis of urban growth and land use changes, which are critical for understanding and addressing environmental challenges in a systematic manner.

The capital of Bangladesh, Dhaka, is a densely populated area with continuous rural-to-urban migration, an expanding metropolitan area, and has emerged as a megacity of more than ten million inhabitants. Chattogram is the second-largest city along the coast which may soon become a megacity with its fast-paced urban growth. Sylhet is the third largest city and selected because it is also experiencing massive urban development. Although studies have documented the land-use change patterns in Bangladesh cities (Abdullah et al., 2019; Arifeen et al., 2021; Xu et al., 2020), they mainly focused on the capital city of Dhaka (Ahmed et al., 2013; Dewan & Yamaguchi, 2009; Dewan et al., 2012; Moniruzzaman et al., 2020). A few studies have focused on the historical land use changes in Chattogram (Abdullah et al., 2022; Hassan & Nazem, 2016) and Sylhet (Gupta, Islam & Hasan, 2018; Hassan, 2017; Uddin, Hossain & Ishaque, 2019;) but their land use classification studies used only a single date image to classify the land use types. Single date scene image classification is a common practice to derive a land use map, but more recently, however, researchers are using image stack composite over a particular time span and incorporating multiple image bands and indices to improve the quality of the derived land use. Although limited studies have been performed in Southeast Asian megacities, Huang et al. (2023) achieved a classification accuracy of 99.4% for Ho

Chi Minh City, Vietnam, by utilizing Landsat 8-OLI image stacks and applying the random forest algorithm, demonstrating the method's effectiveness for urban land use mapping. Other Southeast Asian megacities, such as in Jakarta, Indonesia and Manila, have not explicitly detailed the use of image stacks for land use classification (Murayama et al. 2015). Our study incorporates this newer more advanced methodology adopted from Oliphant et al (2019) using Landsat imagery time-composited over four time-periods over 3-years forming a 44 band image stack for each city and each representative decade to more accurately derive land use maps. This approach reduces the impact of clouds, a significant problem in tropical areas, along with the mixed signatures from natural land surface types and farming practices and enables small spatial patches of land use to be identified.

This study also leveraged the many advantages associated with using Google Earth Engine (GEE) for satellite image processing and analysis. GEE is a free, cloud computing platform that allows convenient and powerful geospatial processing of large volumes of multi-temporal remote sensing data along with many publicly available raster datasets, alleviating the burden of downloading and processing the satellite imagery locally on a computer (Gorelick et al., 2017; Oliphant et al., 2019). GEE has been successfully used for many global and continent-wide land use analyses (Gorelick et al., 2017; Shelestov et al., 2017; Walter & Mondal, 2019).

One additional unique aspect of this study is documenting the uncertainty in the derived land use maps. This is largely absent from land use studies and totally absent from studies in Asia where only the overall accuracy is documented using an error matrix and kappa coefficient. Incorporating uncertainty maps is crucial for understanding classification reliability, particularly in complex urban environments

where land use transitions are frequent and ambiguous. While the use of uncertainty maps remains relatively rare in existing literature, studies such as Rohde (2024) have demonstrated its potential to improve the robustness of land use analysis. Including uncertainty in land use classification results is crucial for ensuring that policymakers and stakeholders can make informed decisions. Sustainable policies often depend on accurate land use information, but inherent uncertainties in classification can affect outcomes, such as for resource allocation, urban planning, or environmental conservation.

2.2 Materials and Methods

2.2.1 Study Area

Bangladesh is a low-lying deltaic country in South Asia bound between 20°34’ to 26°38’N latitude and 88°01’ to 92°41’E longitude with a territory of approximately 147,570 square kilometers (km^2) (Banglapedia, 2021). It shares administrative boundaries with India to the north, east, and west, the Bay of Bengal to the south, and a partial border with Myanmar to the southeast. Bangladesh is the eighth most populous country in the world, with 165 million people in 2022 (BBS, 2022). The population density is 1,119 people per km^2 (BBS, 2022), with 31.5% of residents living in urban areas in 2021 (BBS, 2022). To accommodate an increasing urban population, Bangladesh’s city authorities are planning future development within an extended city boundary. This study compares the development trend in the current city boundaries with the proposed future extension area to document the urban growth patterns. The three largest Bangladeshi cities, including Dhaka, Chattogram (previously called Chittagong), and Sylhet, are selected for this research (Figure 2.1)

to examine the land use change patterns occurring due to urbanization. These three cities are very important socio-economically and differ in their population density and growth rate, land use pattern, topography, and weather.

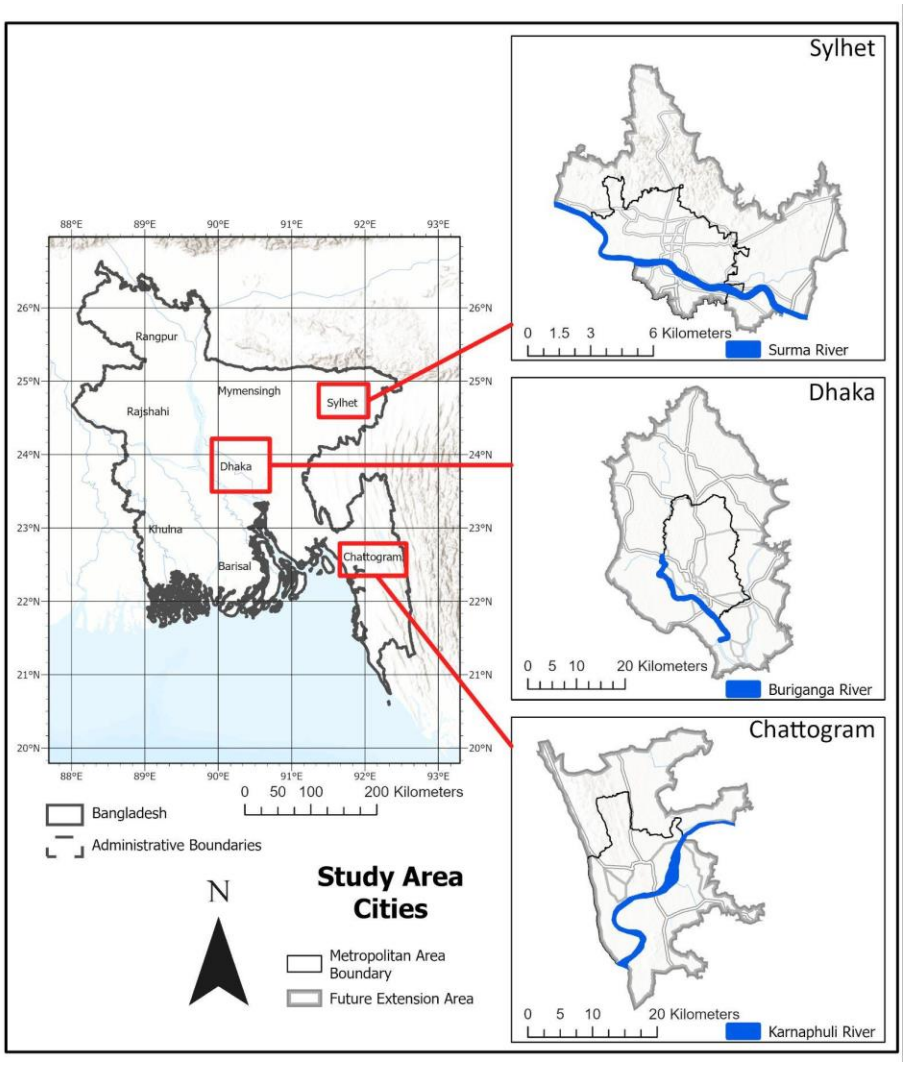

Figure 2.1: Bangladesh administrative boundaries with the location of study areas: Dhaka, Chattogram, and Sylhet, their existing municipal boundaries, planned future extension area, and major rivers.

Dhaka is the capital of Bangladesh and is located near the geographic center of the country (Figure 2.1). It is one of the fastest-growing megacities in the world, occupying more than ten million people (10,278,882) in 2022 (BBS, 2022) in compact urban communities. Dhaka was declared the seventh least livable city in the world in 2022, according to the Global Livability Index, considering stability, healthcare, culture, environment, education, and infrastructure (EIU, 2022). Although the other two largest cities, Chattogram and Sylhet, are not classified as megacities, both have experienced rapid urbanization over the last few decades. Chattogram is the second largest city in Bangladesh and is located along the southeastern coast of Bangladesh (Figure 2.1), with a city population of 3,227,246 in 2022 (BBS, 2022). Sylhet is situated in the northeastern part of the country (Figure 2.1), with a population of 532,426 in 2022 (BBS, 2022), and is also a fast-growing urban area. Dhaka's topography is primarily flat, whereas Sylhet and Chattogram have some highlands in the north and northeast boundaries.

2.2.2 Land Use Classification Method

Remote sensing and GIS technologies are widely used and popular methods in many disciplines to document and monitor land use change. This study utilized Landsat satellite data due to its freely available, long-term record from the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov/), moderate spatial resolution (30 m), and proven effectiveness in numerous land use studies (Ahmed et al., 2013; Islam, Miah & Inoue, 2016; Mukherjee & Singh, 2020; Rahman, 2021; Rai et al., 2017; Walter & Mondal, 2019). Landsat 5 Enhanced Thematic Mapper plus (ETM+) and Landsat 8 Operational Land Imager (OLI) Tier 1 Top of Atmosphere (TOA) reflectance data were selected for 2001, 2011, and 2021 as a representative

year in each decade to derive the land use. We first attempted the image classification of the three cities by creating a one-year cloud-masked median image stack of Landsat imagery for each year. For cloud masking, we used the CFMask algorithm that utilizes QA bands and bitwise operations for cloud detection (Foga et al. 2017). The classification of the median Landsat image stack led to confusion between fallow and cultivated agricultural lands, and floating vegetation and forest. With some experimentation, we were able to increase classification accuracy by using a three-year (1999-2001, 2009-2011, and 2019-2021) time-composited image stack explained below that accounted for spectral and seasonal variations of the different land use types. For example, the overall accuracy of Dhaka city's land use classification using a single-year median image composite was 89% (kappa 0.85), whereas using a multi-date, multi-year, multi-band and indices image stack resulted in an overall accuracy of about 94% (kappa 0.92). We found the same result for Sylhet and Chattogram that the image stack increased the overall accuracy and the kappa coefficient score.

The multi-date, multi-year, multi-band and indices image stack for each representative decade (2001, 2011, 2021) was created following the flowchart in Figure 2.2. All single scene images available within the three-year periods (1999-2001, 2009-2011, and 2019-2021) for each of the three seasons and for the annual cycle were combined to create an image stack for each representative year (2001, 2011, 2021) in order to ensure cloud-free pixels and to account for the greening of the landscape and distinct agricultural practices. Heavy cloud cover was especially problematic during the monsoon season from early June to mid-October (Ahmed and Kim, 2003). Three seasonal and one annual temporal period were selected for creating the image stack based on the climatological seasons impacting the greening of the land

surface and the distinct agricultural practices rather than using the astronomical calendar. The temporal periods include January-April (period 1), May-August (period 2), September-December (period 3), and January-December (period 4) for each representative year. This fourth period captures the inter-annual variability and includes the standard deviation of the Landsat bands and the indices.

The Landsat image bands included in the time-composited image stack were the blue (B), green (G), red (R), near infrared (NIR), shortwave infrared 1 (SWIR1), shortwave infrared 2 (SWIR2), and thermal bands that are useful in differentiating land use types by utilizing optical and thermal information (Walter and Mondal, 2019). In addition to individual Landsat bands, the time-composited image stack included the spectral indices of Normalized Difference Vegetation Index (NDVI), Normalized Difference Built Index (NDBI), Modified Normalized Difference Water Index (MNDWI), and Normalized Difference Bareness Index (NDBaI). The equations for the indices are given by the following equations: NDVI = (NIR - Red)/(NIR+Red) (Ding et al. 2014), NDBI = (SWIR1 - NIR)/(SWIR1+NIR) (Estoque and Murayama, 2015), MNDWI = (Green - SWIR1)/(Green+SWIR1) (Chang et al. 2022), and NDBaI = (SWIR1 - SWIR2)/(SWIR1+ SWIR2) (Zhao and Chen 2005).

The time-composited image stack for the three seasonal periods (period 1-3) include the median of all spectral bands and indices, whereas the fourth period includes the standard deviation of all the bands and indices in the last year (period 4). Using median values avoids the influence of extremes (Walter & Mondal, 2019), and the standard deviation band captures the inter-annual variability providing greater class separability for a given band (Oliphant et al., 2019).

The resulting image stack consists of 11 bands in each temporal segment for each period (1-4), creating a 44-band image stack. This image stack was used as input for a pixel-based random forest (RF) supervised machine learning classification model (Figure 2.2). The RF algorithm has been used successfully for over a decade and has been found to outperform other machine learning algorithms in land use classification (Belgiu & Drăgut, 2016; Oliphant et al., 2019; Walter & Mondal, 2019). GEE and ArcGIS Pro were used for image processing and analysis.

The time-composited images stack (one for each representative year and in each city) were classified into five dominant classes according to Anderson's (1976) Level 1 land use types, including built-up, agriculture, forest, waterbodies, and barren land or bare soil. Built areas are defined as land developed with impervious surfaces such as roads, buildings, and parking lots, even if partially covered by other land uses such as grass and trees. Agricultural areas are fields used for growing and harvesting crops. Forest land use includes areas predominantly covered in trees and not covered by water, and waterbodies are areas covered completely by water year-round. Barren land defines areas with bare soil year-round, such as sandy areas, land surfaces under construction, or low-lying areas filled in for future housing developments.

A post-processing filtering technique was applied to replace isolated pixels with the most common neighboring class. A majority 3 x 3 window filter was applied using ArcGIS Pro, where each classified image pixel is reclassified based on the majority value of the eight neighboring pixels identified using a moving window. This technique removes the erroneous artifacts resulting from the classification and improves the accuracy and visual correctness. The final analysis performed involved quantifying land use changes on a decadal basis. Change detection maps were

generated to visually represent these transformations over the two decades. The classification performance was tested quantitatively using the test data to compute an error matrix. Along with the traditional accuracy measure, we also calculated the multiprobability of each land use class. The individual multiprobability layers were assessed by mapping the probability of greater than or less than 50%. We also assessed each map visually (qualitative assessment) to see how well the classified map corresponded with the real landscape, comparing the classified maps with very high-resolution imagery in Google Earth Engine base map and Google Earth Pro's timeline imagery.

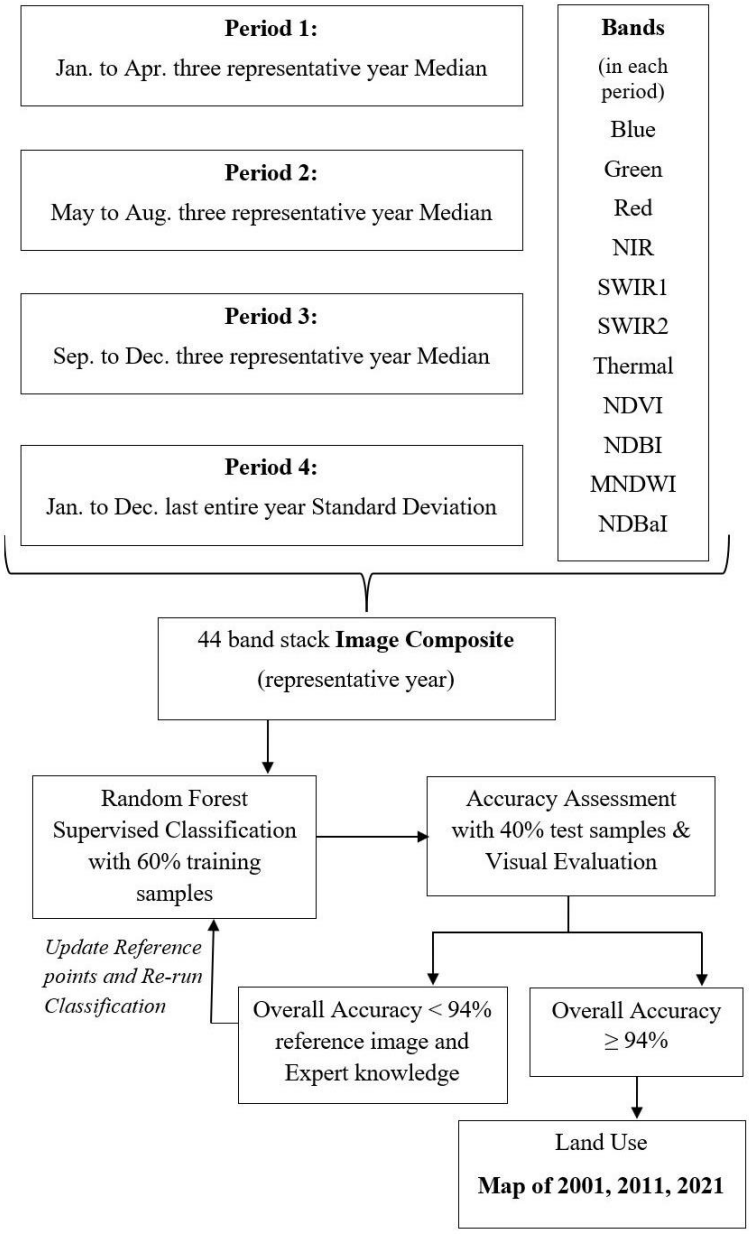

Figure 2.2: Flowchart of the methodology.

2.2.3 Reference Data for Classification and Accuracy Assessment

Although field data collection is the ideal manner to collect reference data necessary for image classification, this study relied on visual assessments of high-

resolution remotely sensed data because of the difficulty in studying a large geographic area, and due to time and financial constraints. Additionally, remote sensing imagery allowed us to capture past land use conditions by using Google Earth Pro's timeline images for 2001 and 2011 and the Google Earth Engine (GEE) base map image for 2021. For the land use classification and accuracy assessment, a total of 300 reference points (both training and test points) were selected from Google Earth Pro's high-resolution images of each of the three cities for each decadal represented year. Although not randomly generated, the locations of the reference points were selected to geographically sample the Bangladesh cities by choosing sites that incorporate the subtle variations in each land use type due to the highly variable urban landscape while also systematically sampling the spatial extent of each city. The selection of reference points per land use class follows the 3 by 3 cell block rule (90-m x 90-m areas), defining the center pixel and its three neighbor pixels in the block as the same land use. The first author's personal experience and familiarity with the study areas greatly facilitated the selection of reference points. The reference points were divided into two parts: training and test points. The training points (60% of the total reference points) were used to train the RF classifier algorithm and run the image classification. The remaining 40% of the points (test points) were used to assess the accuracy of the image classification for each urban center.

An error matrix was generated with the values of overall accuracy, as well as with the producer's and user's accuracy and the kappa coefficient score. The derived land use maps were also evaluated using the RF classifier algorithm probabilistic outputs called 'multiprobability' method in GEE (ee.Classifier.setOutputMode | Google Earth Engine, n.d.). The multiprobability analysis outputs a set of probability

layers, where each layer represents the likelihood of a pixel belonging to a specific land use class. These probabilities indicate the classifier's confidence in assigning each pixel to a particular class, helping to identify areas of high uncertainty or class overlap. Uncertainty maps were prepared for each city and year by displaying areas of higher than and less than 50% probability (Figure 2.3-2.5). Such maps are invaluable for assessing the reliability of classification outcomes, providing critical insights to guide further analysis, refinement, and the effective use of land use information in policy-making decisions.

2.3 Results

2.3.1 Accuracy Assessment

Using the multi-date, multi-year, multi-band and indices time-composited image stack for each representative decade, the overall accuracy values were greater than 94% (Table 2.1), and the kappa coefficient values exceeded 0.92 for each urban area and representative decade year. Our discussion focuses on the largest inaccuracies in the classification by investigating the accuracy assessment (Table 2.2a and b) and the multiprobability analyses (Figure 2.3-2.5).

Table 2.1: Overall accuracy of the classified map in each year per study area.

Overall Accuracy	**2001**	**2011**	**2021**
Dhaka	95%	100%	94%
Chattogram	98%	98%	98%
Sylhet	100%	96%	96%

Dhaka's derived land use maps produced the lowest accuracies overall. The set of probability layers for each derived land use map (each layer represents the

likelihood of a pixel belonging to a specific class) and a qualitative analysis were carefully examined to identify areas of high uncertainty and class overlap. Equivalent maps were examined for the other two cities as well, but these maps were not included in the study. We found the greatest confusion in the Dhaka agriculture class being confused as another land use type in 2001. The reason for the misclassification of the agriculture class in 2001 was due to some land areas being uncultivated and therefore having a similar spectral signature to the built-up and barren class such as the northeast part of central Dhaka. The agriculture class was also confused with deep and shallow water bodies containing floating vegetation. The floating vegetation was recognized as healthy vegetation with high spectral reflectance in the near-infrared band and low reflectance in the red band similar to the mature agricultural crops. In 2001, the northeast part of Dhaka was misclassified as built-up while it had more probability to be forest or agriculture as we see in Figure 2.3.

In 2021, the agricultural and forest classes were difficult to distinguish for Dhaka due to the similar spectral reflectance of healthy vegetation (Table 2.2b). Both land use types show high reflectance in the near-infrared band (B5) and low red reflectance (B4), leading to spectral similarity and their misclassification. For example, the southwest part of the current municipal boundary was classified correctly as agricultural land, but the southeast area had some misclassification. Despite these misclassifications, our classifications all yielded high accuracies suitable for the analysis of urban growth and changes over the last 20 years for all three cities.

Table 2.2a: Accuracy assessment for the 2001 classified map of Dhaka city.

		Reference Data					User's Accuracy
		Built-up	Agriculture	Forest	Water	Barren	
Classified Data	Built-up	31	2	0	0	0	93.9%
	Agriculture	0	29	0	1	0	96.7%
	Forest	0	0	18	0	0	100%
	Water	0	1	0	15	1	88.2%
	Barren	0	1	0	0	21	95.5%
Producer's Accuracy		100%	87.9%	100%	93.8%	95.5%	
						Overall Accuracy	**95%**
						Kappa Coefficient	**0.94**

Table 2.2b: Accuracy assessment for the 2021 classified map of Dhaka city.

		Reference Data					User's Accuracy
		Built-up	Agriculture	Forest	Water	Barren	
Classified Data	Built-up	43	0	0	0	1	97.7%
	Agriculture	0	10	2	0	0	83.3%
	Forest	0	1	18	0	0	94.7%
	Water	0	0	0	16	0	100%
	Barren	3	0	0	0	20	87%
Producer's Accuracy			93.5%	90.9%	90%	100%	95.2%
						Overall Accuracy	**93.8%**
						Kappa Coefficient	**0.92**

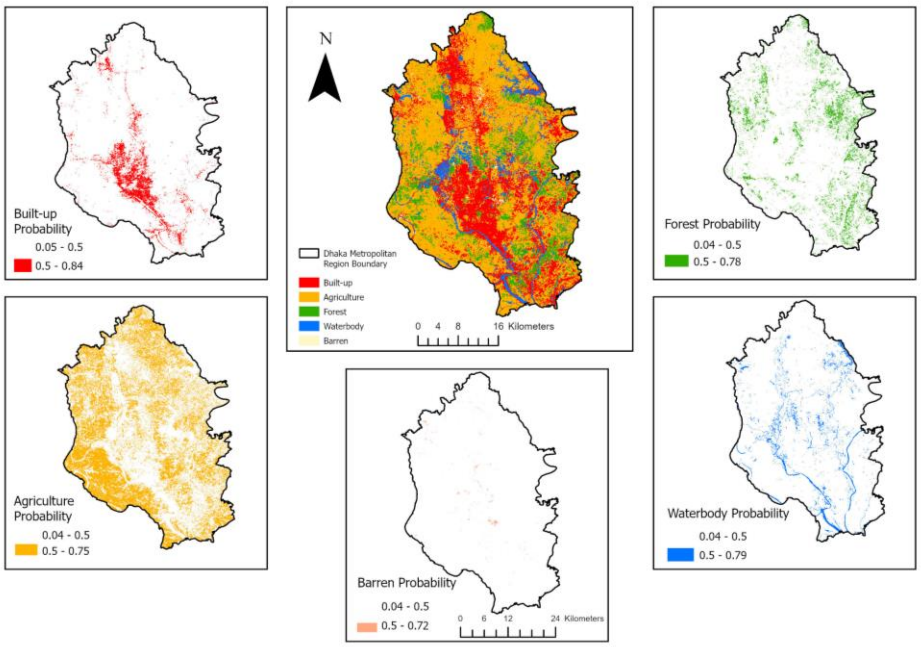

Figure 2.3: Uncertainty Map of Land Use Classification of Dhaka in 2001.

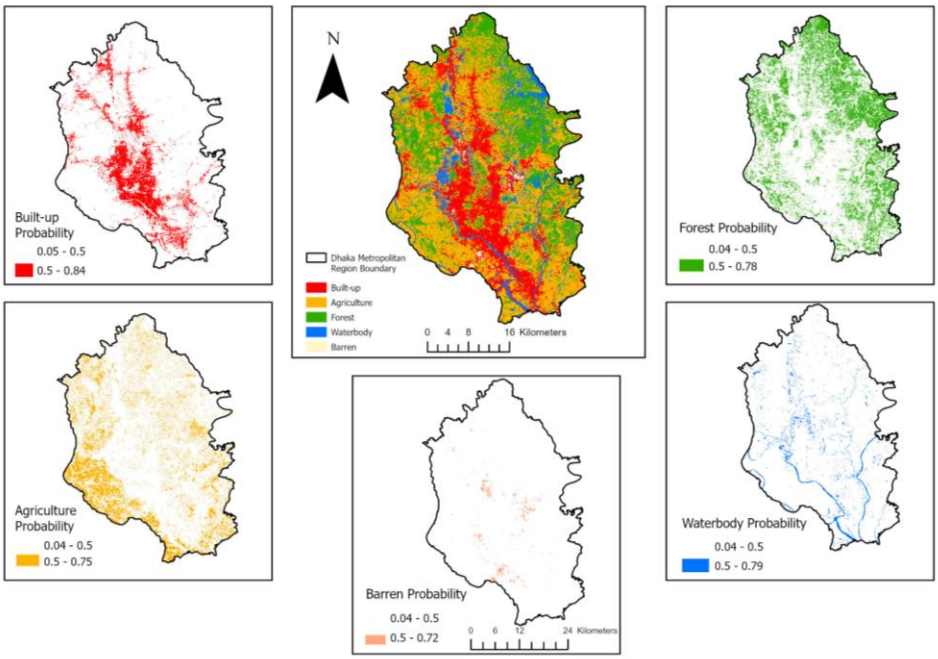

Figure 2.4: Uncertainty Map of Land Use Classification of Dhaka in 2011.

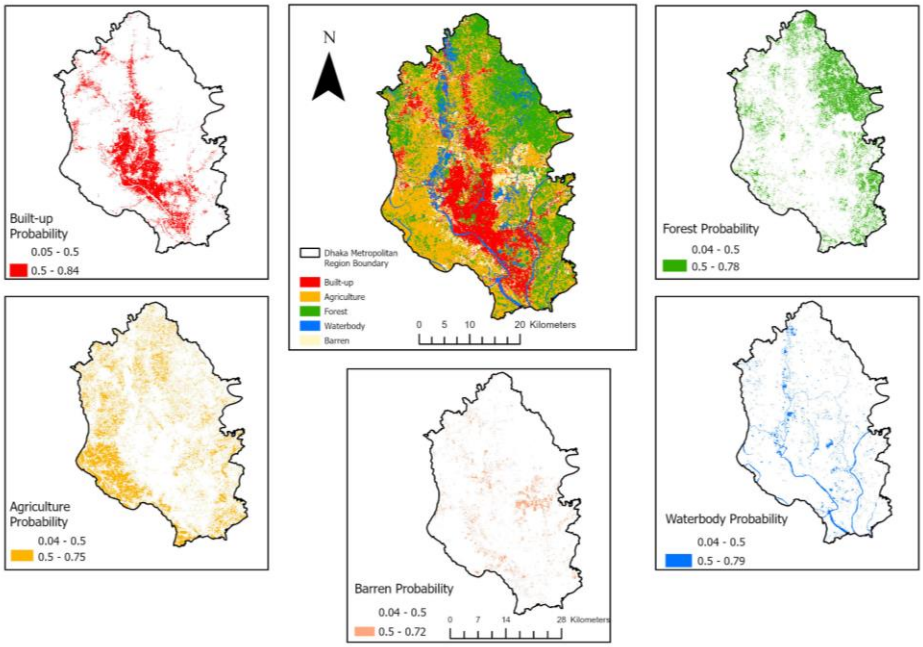

Figure 2.5: Uncertainty Map of Land Use Classification of Dhaka in 2021.

2.3.2 Spatiotemporal Land Use Changes over the Last Two Decades

The cities of Dhaka, Chattogram, and Sylhet are the three largest cities by total population and represent major urban cores of business, commerce, political, and administrative activities in Bangladesh. The unique geographical settings, along with its administrative and economic functions, have influenced the land use changes over the last 20 years. Figure 2.6 shows the land use distribution in Dhaka, Chattogram, and Sylhet for the three time periods considered in this study. These land use classification maps illustrate the radical transformation of the landscape from 2001 to the present. The maps and summary graphs (Figures 2.7–2.9) clearly show a significant increase in built-up areas and a decrease in agricultural lands over this period. Other observable patterns are the small changes in water and barren land areas.

2.3.2.1 Land Use Change Pattern in Dhaka City

Over the past 20 years, the city of Dhaka has dramatically densified along the Buriganga River and grown northeastward from 22% built-up area to now occupying almost half of the current city boundary (47.4%) (Figures 2.6 and 2.7). The urbanization rate of 1.7% per year during the first decade slightly decreased to 0.9% per year from 2011 to 2021. Our findings also indicate the major urban growth trajectory radiating northward from the urban core into the proposed city expanded boundary (Figure 2.6). There is also densification (increased density of population and infrastructure) occurring southward of the current city boundary, connecting the peripheral suburban areas to accommodate the increased urban population.

Dhaka's impressive urban growth occurred largely at the expense of agricultural land. In 2001, agricultural areas covered approximately 60% of the city area, and today only 22% of the area is agriculture. Water bodies encompassed 12.6% of the total area in 2001 also declined to 8% in 2021, and barren land has continually increased since 2001 (Figures 2.6 and 2.7). This growth has caused many low-lying areas to be filled, driven by the scarcity of land and the demand for housing for the growing urban population (RAJUK, 2022).

The land use analysis revealed that the forested land increased during the first decade (4.8% in 2001 to 27% in 2011) but declined to 10% during the second decade (2011 to 2021). In the first decade, the increase is attributed to the afforestation program established by a 1994 Bangladesh forest policy (Reddy et al., 2018). This policy appears to have improved the extent and quality of forest cover, but it was not sustainable in the long term. In the recent decade, forest cover declined due to the large demand for infrastructure development.

The land use maps illustrate Dhaka city area growth from a compact urban area surrounded by large agricultural areas in 2001 to a conglomerate urban area of concrete and impervious surfaces covering more than half of the city today. The highly fragmented forested areas are visible, with the exception of the large, intact Bhawal National Park in the north. The maps also show the water bodies have been filled in with sands so development can take place. One example of such an area is the eastern part of central Dhaka called Purbachal Residential Model Town that has been classified as barren.

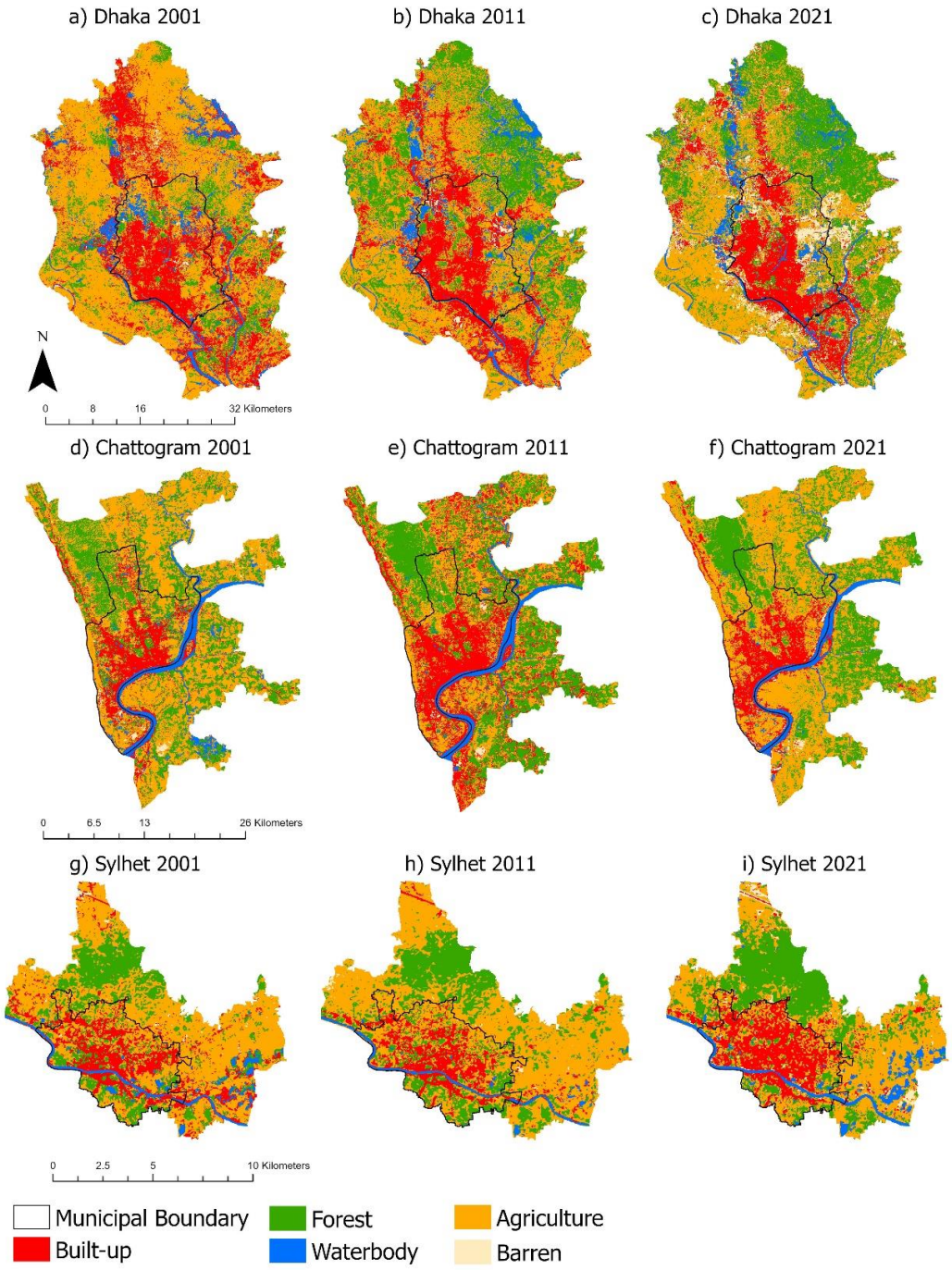

Figure 2.6: Spatial distribution of land use extents in Dhaka, Chattogram, and Sylhet City during the last two decades.

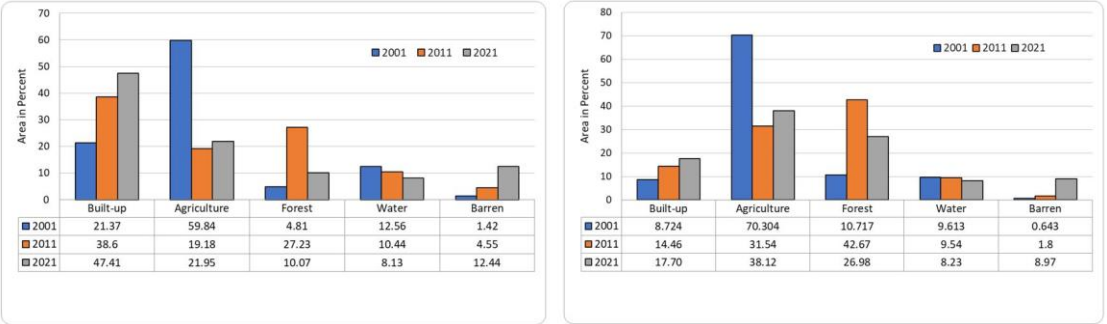

Figure 2.7: Land use composition in the present city (left chart) and proposed extension area (right chart) of Dhaka metropolitan area over the last two decades.

2.3.2.2 Land Use Change Pattern in Chattogram City

Located next to the Bay of Bengal, the coastal city of Chattogram is the major port city of Bangladesh. The city grew from the southern part of the current municipality along the Karnaphuli River. Chattogram is less urbanized than Dhaka (Figures 2.7 and 2.8), but its land use change over the past two decades are comparable. Built-up areas increased from 19% in 2001 to 37% in 2021, agricultural land decreased from 57% to 43%, and forests saw a 17% increase in the first decade, followed by a significant 19.5% decline in the second decade. Water and barren land use remained rather steady over the last twenty-year period (Figure 2.8). The large increase in forest cover from 2001 to 2010 was further analyzed by visually checking the 2011 land use map with high-resolution Google Earth Pro's timeline imagery. We found some of the agricultural lands were misclassified as forest cover due to very similar spectral signatures that contributed to an increase in the first decade.

Similar changes in all land use appear when analyzing the future city expansion area (Figure 2.8). The urban growth is occurring from the city center area northward, restricted by the Karnaphuli River on the city's southern boundary and

following the major corridor along the western edge of the future city boundary. An additional observable feature is the large forested area evident in the northern area of the extension municipal boundary since 2001. This area is dominated by a national preserve and has remained as a forest. Overall, the growth in Chattogram resulted in an urbanization rate of 1.1% per year from 2001 to 2011 and 0.7% per year from 2011 to 2021.

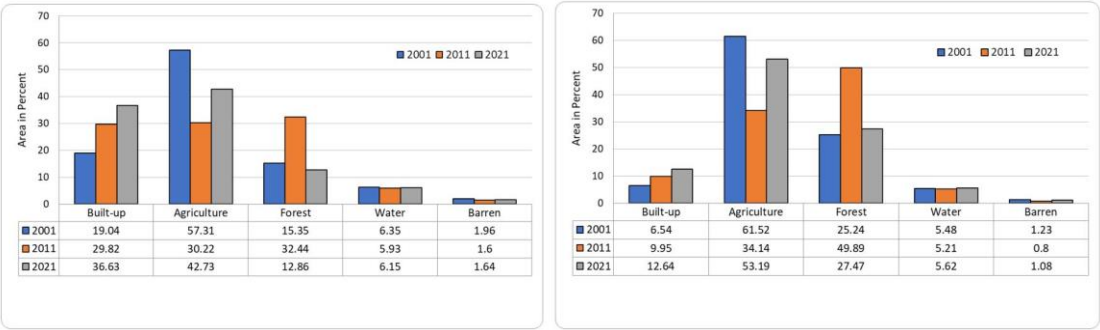

Figure 2.8: Land use composition in present city (left chart) and proposed extension area (right chart) of Chattogram metropolitan area over the last two decades.

2.3.2.3 Land Use Change Pattern in Sylhet City

Sylhet experienced faster urban development than Dhaka and Chattogram, as shown in Figure 2.6, with most of the urbanization confined to the current city boundary, resulting in densification of the urban area. Sylhet city developed along the northern banks of the Surma river and expanded to the northeast following the major highway. Currently, new urban development is occurring by replacing agricultural land with built-up areas. Built-up land covered 49% of the existing municipality in 2021, increasing from 28% in 2001. The urbanization rate was 0.9% per year from

2001 to 2011 and jumped to 1.2% per year from 2011 to 2021. Agriculture was the dominant land use in 2001 (~54%), but at present, it covers less than 32% of Sylhet municipality. The forest area is currently 11% of the city boundary. Water bodies remained nearly constant over the last two decades, similar to Chattogram. Sylhet also contains a minimal barren area, just like the other two cities.

The surrounding periphery of the future planned development area contains much less built-up area, but the built-up percentage had nearly doubled from 10% in 2001 to 19% in 2021 (Figure 2.9). The agriculture class decreased by 27% from 2001 to 2011. Forest decreased by 7% from 2001 to 2011, and then increased dramatically to 15% in 2021. This large increase in greenness from 2011 to 2021 was suspected as being misclassified and further investigated qualitatively and examining the land use class probability layers. We found that the image classifier misclassified agriculture as forests due to spectral signatures of tea plantations being confused as forests (Mamun, 2019). Water bodies and barren areas were mostly constant throughout the study period.

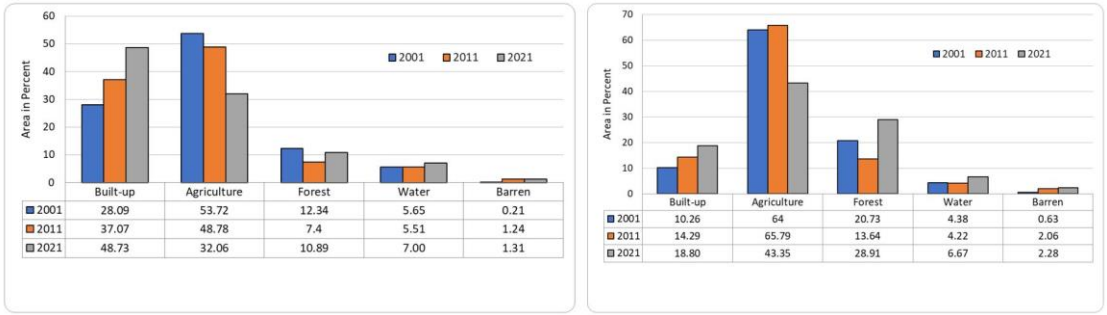

Figure 2.9: Land use composition in present city (left chart) and proposed extension area (right chart) of Sylhet metropolitan area over the last two decades.

2.3.3 Land Use Change Detection in the Study Areas

Extensive land use changes have occurred in Dhaka, Chattogram, and Sylhet (Figure 2.10) in the last 20 years. Dhaka experienced the most significant change, with 65% of the area undergoing land use conversion, followed by Sylhet at 52% and Chattogram at 48% alteration in the land use.

Much of Dhaka's metropolitan area has changed, while a speckled pattern of change/no change occurred across the proposed future expansion boundary area (Figure 2.10). Only some forested areas in Sylhet (Tilagor Reserve Forest, Khadimnagar National Park, Forestry department plantation zone), wooded areas in the hilly region of the northern zones of Chattogram, and the major rivers in three study areas remained unchanged throughout the study time periods.

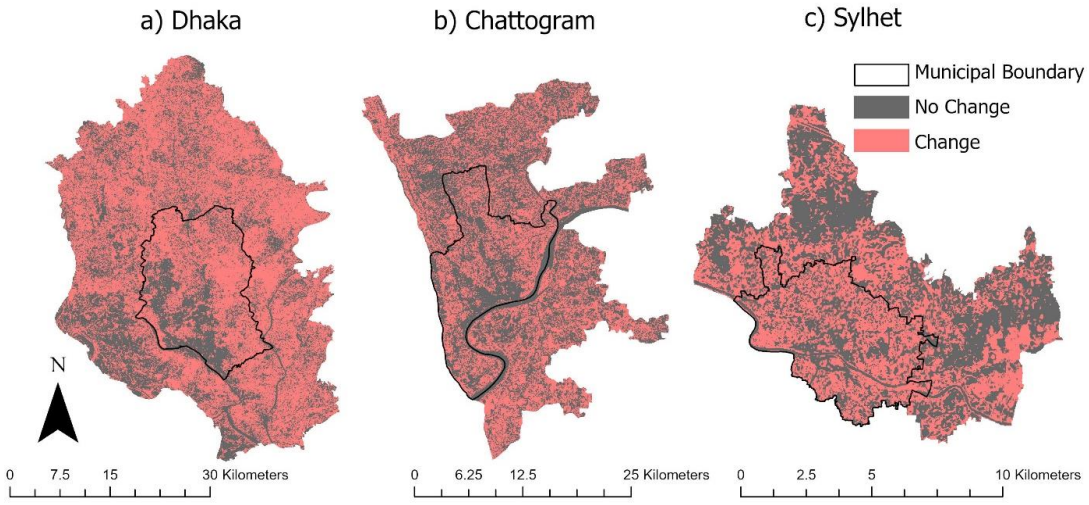

Figure 2.10: Land use change detection in three study areas (Dhaka, Chattogram, and Sylhet City).

2.4 Discussion

Urban land area worldwide expanded 2.9-fold between 1985 and 2015, with significant growth observed in Europe, Asia, and North America (Zhou et al., 2022). Asian cities are poorly understood and need attention as this region accounts for 35% of the total population, resides on less than 2% of the world's area, and has the highest population growth rate (Vadrevu 2018). This study specifically focused on Bangladesh three cities (Dhaka, Chattogram, and Sylhet) where Dhaka is in need of immediate attention as it's classified as a megacity and the seventh least livable city in the world. The two second largest cities are also experiencing rapid growth and urbanization challenges.

Over the last 20 years, Dhaka, Chattogram, and Sylhet expanded and densified along the major river corridors and followed the major infrastructures of the cities' airports, educational institutions, and road networks. Dhaka has expanded in northsouth direction along the major road networks and the Buriganga river. The urbanization in Chattogram has largely densified and expanded northward from the Karnafuli river that forms the city's southeast boundary. Sylhet's urban growth is comparable to Dhaka and Chattogram with densification occurring largely in the areas north of the Surma river. Urban growth is happening at the cost of non-urban land use classes with vegetated areas and water bodies replaced by built-up areas. In the last 20 years, the megacity of Dhaka has experienced dramatic land surface change, with half of the core Dhaka city boundary urbanized today, and the conversion is most likely to continue in the future due to the fast-growing urban population and its increasing need for housing and other amenities. Our study found that 18% of Dhaka's proposed extension area (~48% of the current city), 13% of Chattogram's extension area (~37% of the existing municipal boundary), and 19% of Sylhet's extension area (~49% of the

current city boundary) are already urbanized. This highlights the need for authorities to plan and monitor future growth in these areas to ensure sustainable urban development.

This rapid urbanization trend found in our study complements previous studies. Considering only the core municipality of Dhaka, Ahmed et al. (2013) found that 37% of the city was classified as built-up in 2009 and projected 49% built-up area coverage in 2021, which is very compatible with our study of 38.6% built-up area in 2011 and 48% area built-up in 2021. Hassan & Nazem (2016) recorded 56% land use change in Chattogram over the last 36 years, which is also comparable to our findings of 48% change in the last 20 years. Our study found densification of the Sylhet city and urbanization extending to the northeast within the proposed city boundary, while Gupta et al. (2018) reported that the city's urbanization extended in the northeast direction from the city center after 2011. Moreover, our findings resonate with broader urbanization patterns observed in other mega cities. Cities like Beijing and Bangkok, despite their high built-up densities, exhibit rapid growth rates comparable to cities such as Dhaka and Nairobi, Kenya which have lower building densities but are experiencing similarly accelerated growth. This trend suggests that cities with initially lower built-up densities, particularly in developing regions, are urbanizing at an increasingly fast pace, reflecting a dynamic shift in global urban expansion (Murayama et al., 2015).

Across all three cities, we observed that vegetation and water bodies are being replaced by built-up areas. If the current urbanization trend persists, impervious surfaces will continue to expand, posing a significant threat to human health, energy consumption, and natural ecosystems. Green vegetation and water bodies play a vital

role in maintaining better environmental conditions (Heidt and Neef 2008). Vegetated areas help to cool the environment and reduce the urban heat island through shading and evapotranspiration along with filtering pollutants. Therefore, the municipal authorities must closely monitor the future development of the proposed extension area so that the suburban periphery maintains a balance between the green and impervious surfaces. Dhaka is currently an unlivable city (EIU 2022). Its growth has been disorganized, unplanned, and uncontrolled contributing to many socio-economic and environmental problems. Chattogram and Sylhet city are greener than Dhaka, but the rapid urbanization of these cities threatens the greenness of these areas. Proper planning is crucial to manage the drastic changes in land use patterns; without it, both environmental quality and human health will inevitably decline. Planners and policymakers need to develop plans to meet the future demands of the increased urban population in a sustainable manner. One example of the importance of the implementation of green policy is the increase in forested areas documented from 2000 to 2011 due to an afforestation program undertaken by the Bangladesh Government (Reddy et al. 2018). However, this increase was not maintained into the second decade. Mitigation strategies to address the negative impacts of urbanization in these cities should include promoting tree planting, establishing green corridors, and protecting existing green spaces (Song et al. 2018). Additionally, policies should aim to increase the sky view factor (SVF) in the urban environment to improve air circulation, heat dissipation, daylight access, and lessen the impact of the UHI effect (Lu et al. 2023; Manoli et al. 2019). Furthermore, enhancing evapotranspiration through green roofs, irrigation, and tree planting can help mitigate the UHI effect, though care should be taken to avoid potential water shortages and decreased thermal

comfort due to rising humidity (Bastin et al. 2019; Jendritzky et al. 2012; Zhou et al. 2022).

2.5 Conclusion

This study analyzed the urban growth rate and expansion patterns over the past two decades in three cities of the rapidly developing country of Bangladesh: the megacity Dhaka, the second-largest city Chattogram, and the rapidly urbanizing area of Sylhet. Our study documents and compares the urban growth pattern within the current municipal boundary and the proposed future extension area that has not been done in previous studies. By performing a land use classification using freely available Landsat satellite images, the decadal land use and change analysis documents the drastic land use pattern change in all three cities since 2000. The study incorporated a unique approach to classifying the diverse urban landscape by time, combining the Landsat imagery over four time periods coincident with the annual cycle and agricultural practices, and over three years to reduce the impact of clouds. The time-composited image stack that included 44 bands for each decade was classified using the well-documented and successful pixel-based Random Forest (RF) supervised classification method leveraging the Google Earth Engine (GEE) cloud platform. Overall, the RF classifier was able to accurately distinguish different land use types with greater than 94% overall image classification accuracy and more than 0.92 kappa coefficient for all three cities and for each representative decade. Careful qualitative analysis of the results and examination of the probability layers for each land use class found some inaccuracies with the derived land use. Inaccuracies were found with the confusion of some agricultural and forest areas due to their similar spectral reflectance of healthy vegetation. In particular, Sylhet had increased growth in tea plantations

which were confused with forest cover. Another misclassification occurred with water bodies being classified as vegetated areas due to floating vegetation on water. Although this study tried to solve these misclassifications by adding more reference points in those areas to enhance the classification, some locations still were misclassified. This is attributed to the heterogeneous urban landscape and the medium resolution of Landsat imagery. The probability land use class layers highlight areas of greatest uncertainty, offering valuable insights for policy makers to make informed decisions.

Our study includes analyses of the existing municipal boundaries and the proposed future extension areas that the municipal authorities have delineated to accommodate the large urban population migration and control the disorganized urban development. In particular, Dhaka has developed a long-term master plan to ensure sustainable urban development. The rapid urban growth has placed strains on local authorities to follow the master plan to ensure proper management and utilize its limited land resources. Hence the geospatial information generated from this study will assist planners, stockholders, and other interested groups to better understand the urban growth dynamics and land use change patterns at the city level. Further, the results serve as a guide for developing planning strategies and restoration programs to reduce the adverse impacts of unplanned city growth and design achievable goals for the future, for not only the current metropolitan area, but also very important for the proposed expansion boundary extent.

Our study provides a comparative analysis of urban growth and landscape change over the last two decades in Bangladesh's three largest cities, Dhaka, Chattogram, and Sylhet, using advanced geospatial techniques and satellite data on the

Google Earth Engine (GEE) platform. Unlike prior studies that often focused on individual cities or used single scene (date) imagery, our work incorporates a multi-temporal, multi-band and -indices time-composited image stack, enhancing classification accuracy above 94%. This comprehensive analysis documents how unplanned urban expansion has significantly altered the land use patterns, threatening vital ecosystem services in a rapidly urbanizing Global South context. We contextualize our findings within broader global urbanization trends, showing how similar challenges such as urban heat islands, flooding, biodiversity loss, and degradation of natural habitats manifest in diverse settings. The study contributes original insights into the spatial dynamics of urban growth in a developing country with comparison to other studies in the Global South to emphasize the urgent need for sustainable urban planning to mitigate the adverse effects of uncontrolled urbanization.

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Chapter 3

INVESTIGATING THE ATMOSPHERIC AND SURFACE URBAN HEAT ISLAND (UHI) IN BANGLADESH: A CASE STUDY OF THREE CITIES (DHAKA, CHATTOGRAM, AND SYLHET)

3.1 Introduction

When an urbanized metropolitan area generates a microclimate with warmer temperatures than surrounding rural areas, the urban area behaves like a heat island, and this effect is known as the Urban Heat Island (UHI) (Kershaw, 2017; Liu & Zhang, 2011; Trenberth, 2004). In 1818, Luke Howard first described the concept of the UHI by measuring 2ºC temperature difference between London and its surroundings, defining the existence of an urban microclimate (Howard, 1833; Kershaw, 2017). The air temperature of a city with 1 million people or more can be 1-3°C (1.8-5.4°F) warmer than its surroundings (Oke, 1997), and on a clear, calm night, the temperature difference can be as much as 12°C (22°F) (Oke, 1987).

Many factors contribute to the development of the UHI, with urbanization considered one of the most significant factors as it is the main driver of land use change, replacing natural land surfaces with the built environment dominated by asphalt and concrete. Cities typically have lower albedos absorbing more solar radiation and experience greater heat retention compared to non-urban areas (Hidore et al., 2010). City materials absorb energy during the day and continue to radiate heat after sunset, raising the temperature particularly at night (Hidore et al., 2010; Kershaw, 2017; Patz et al., 2005). Cities also lack water for evaporative cooling

(Sheng et al., 2009). Tall buildings and narrow streets trap heat and reduce airflow. Waste heat from automobile use, industrial processes, and extensive use of air conditioning during hot weather exacerbates the situation by adding warmth (Jones et al., 1990; Sheng et al., 2009). In addition to temperature, humidity is a critical factor in assessing human comfort, as it directly affects how the human body feels when exposed to different heat and humidity conditions (Wang et al., 2023; Manoli et al., 2019). Higher humidity correlates with increased discomfort, which can amplify UHI intensity, particularly at night when urban areas retain more heat (Wang et al., 2023).

An urban heat island is detected by observing air temperature in the lower atmosphere, called the atmospheric urban heat island (AUHI), or measuring the land surface temperature (LST) at the surface level, referred to as the surface urban heat island (SUHI) (Dewan et al., 2021; Hu & Brunsell, 2015). The UHI varies across the urban area according to the size and proximity of buildings, the presence of vegetation and green spaces, and water bodies (Kershaw, 2017). The urban core is usually considerably warmer with more impervious surfaces (Berdahl & Bretz, 1997; Souch & Grimmond, 2014). As vegetation decreases, the LST increases because the green vegetation works as a natural cooling system which is lost or greatly reduced (Weng & Lu, 2008). Waterbodies also create cooler areas within a city.

Studies over the past 100 years include various methods to observe UHI, its effects and consequences, and mitigation strategies. Earlier studies were mainly based on the observed air temperature (Coseo & Larsen, 2014; Oke, 1987; Parker, 2010). With the advancement of remote sensing technologies over the past 40 years, satellite and airborne images are more commonly used to derive UHI based on derived land surface temperature (LST) (Gallo & Tarpley, 1996; Streutker, 2003). These satellite-

based studies have relied heavily on the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High-Resolution Radiometer (AVHRR), Landsat Multispectral Scanner (MSS), Enhanced Thematic Mapper Plus (ETM+), Thermal Infrared Sensor (TIRS) and Operational Land Imager (OLI) instruments, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Terra, and Moderate Resolution Imaging Spectroradiometer (MODIS) Terra, MODIS Aqua. The NOAA AVHRR satellite data (Stathopoulou et al., 2004; Streutker, 2003) was used to derive LST at regional scales and consequently measure UHI based on differences in surface temperatures (Gallo & Owen, 1998). Many studies used MODIS satellite data to measure UHI (Chakraborty & Lee, 2019; Dewan et al., 2021; Hu & Brunsell, 2015; Zhou et al., 2014). At smaller geographical extents, the Landsat series of instruments (MSS, TM, ETM+, TIRS & OLI) have often been utilized (Chen et al., 2006; Liu & Zhang, 2011; Rinner & Hussain, 2011; Weng & Lu, 2008; Xiong et al., 2012) to measure the LST, along with detailed studies of land cover change over time.

These studies have occurred all over the world and documented the intensity of LST changes and correlated them with land use patterns and their changes, rates of urbanization associated with building density, and composition of built-up areas, vegetation, and water bodies. For example, Chen et al. (2006) studied the rapid urbanization in southern China's Guangdong Province using Landsat TM and ETM+ images. They found higher temperatures for construction, semi-bare, and bare land compared to other surface types. Another study by Xiong et al. (2012) in southern China evaluated Landsat TM/ETM+ images and different indices (NDVI - Normalized Difference Vegetation Index and NDBI -Normalized Difference Built-up Index) and documented the built-up areas, densely populated zones, and heavily industrialized

districts had higher temperatures than other areas. Weng and Yang (2004) used Landsat TM images to produce land use and LST maps, concluding that low vegetation coverage is a key contributor to the UHI effect in Guangzhou, China. Lo and Quattrochi (2003) examined the Atlanta metropolitan area in Georgia, USA, and found the conversion of rural to urban areas resulted in a significant UHI effect. Imhoff et al. (2010) conducted a study across various cities in the USA using satellite imagery and found a positive correlation between the extent of impervious surfaces and UHI intensity. Studies show that UHI intensifies with increasing population density and building height, and it varies based on climatic regions. For instance, urban areas in arid and semi-arid climates show stronger UHI effects than those in temperate regions due to the greater contrast in moisture availability between rural and urban land (Imhoff et al., 2010).

Many cities in developed and developing countries are experiencing the adverse effects of UHI. Bangladesh cities are no exception. Many studies have examined satellite derived LST changes in the cities of Bangladesh (Abdullah et al., 2022; Ahmed et al., 2013; Dewan & Corner, 2014; Gazi et al., 2021; Imran et al., 2021; Kafy et al., 2021; Kafy et al., 2020; Miah et al., 2023), but very few studies have focused on the UHI intensities in urbanized areas. Recently, Dewan et al. (2021) studied SUHI intensity by comparing MODIS day and night LST data from 2000 to 2019 in five major cities of Bangladesh. They found greater SUHI in Dhaka and Chattogram, with the daytime SUHI larger than the nighttime SUHI.

Our study makes a significant contribution to recent UHI research in developing Asian cities by focusing on both the AUHI and SUHI, concentrating specifically on the three largest cities in Bangladesh, and extending the time frame to

2023. We also introduce humidity into the analysis—an often-overlooked factor in long-term UHI studies, especially in tropical cities, where the combination of high temperatures and humidity can create dangerously uncomfortable conditions for human health. Additionally, unlike many studies that rely on municipal boundaries encompassing a mix of land use types, we explicitly define urbanized versus non-urbanized areas, providing a more precise comparison.

This research examines the urban heat island (UHI) intensity across the three largest cities in Bangladesh—Dhaka, Chattogram (formerly Chittagong), and Sylhet—using air temperature data and medium-resolution satellite imagery (thermal band for LST). We focus on analyzing the magnitude of the AUHI (over 35 years) and SUHI (over 20 years) in these cities, highlighting significant differences and linking these trends to changes in land use. The findings provide valuable insights for future urban planning aimed at mitigating UHI effects and other urban hazards.

3.2 Materials and Methods

3.2.1 Study Area

This study is conducted in three cities of Bangladesh (Figure 3.1), which is located in South Asia between 20°34’ to 26°38’N and 88°01’ to 92°41’E. The climate in Bangladesh is influenced by its proximity to the Bay of Bengal, which significantly impacts its weather patterns. Bangladesh experiences a tropical monsoon climate (Köppen: Am) characterized by a distinct hot, humid summer, a wet, rainy monsoon season, and a cooler, drier winter. Bangladesh's climate is divided into four seasons: pre-monsoon summer (March-May), monsoon (June-September), post-monsoon (October-November), and winter (December-February) (Choudhury, 2008; Hossain et

al., 2014). Summers in Bangladesh are characterized by high temperatures and humidity, where daytime temperatures often reach above 30°C (86°F) and occasionally exceed 40°C (104°F) in some areas. The winter season is milder with cooler temperatures and lower humidity levels with daytime temperatures generally ranging from 10°C to 20°C (50°F to 68°F).

Bangladesh has experienced rapid growth in urban areas over recent years (Hassan, 2017), and consequently, the UHI phenomenon has grown notably more severe in cities across Bangladesh. To examine the UHI, the three largest Bangladesh cities - Dhaka, Chattogram, and Sylhet - are selected for this research. Figure 3.1 shows their location with the current land use pattern and the location of the observed weather stations.

These three cities hold significant socio-economic importance and exhibit variations in the factors influencing the growth of the UHI, including the population density and growth rate, land use patterns, topography, and climate. Dhaka, the capital and mega city, is located in the central part of the country and acts as a main hub for all major activities (economic, political, administrative, and cultural). Dhaka contains more than ten million people (10,278,882) as of 2022 (BBS, 2022). Chattogram, the commercial capital and second-largest city in Bangladesh is positioned along the southeastern coastline of the country, boasting a city population of 3,227,246 in 2022 (BBS, 2022). In contrast, Sylhet is the next largest city located in the northeastern region, with a population of 532,426 in 2022 (BBS, 2022) and experiencing rapid urban development. The urban population in all three cities is growing quickly, and to accommodate the rapid growth, Bangladesh's municipal authorities are planning to extend the city boundaries, as displayed in Figure 3.1. This study considers the current

municipal boundaries with the planned future extension area in the periphery to document the UHI patterns occurring due to urbanization. The rapid urbanization of Bangladesh cities has intensified existing challenges, particularly those related to environmental degradation and public health. The exacerbated problems, driven by factors like the UHI effect, pose a severe threat to the well-being of the population. Recognizing this urgency, there is a critical need to thoroughly explored the spatiotemporal changes in UHI intensity, as this research can provide valuable insights to inform targeted interventions and foster sustainable solutions for the ongoing issues plaguing the development of these cities.

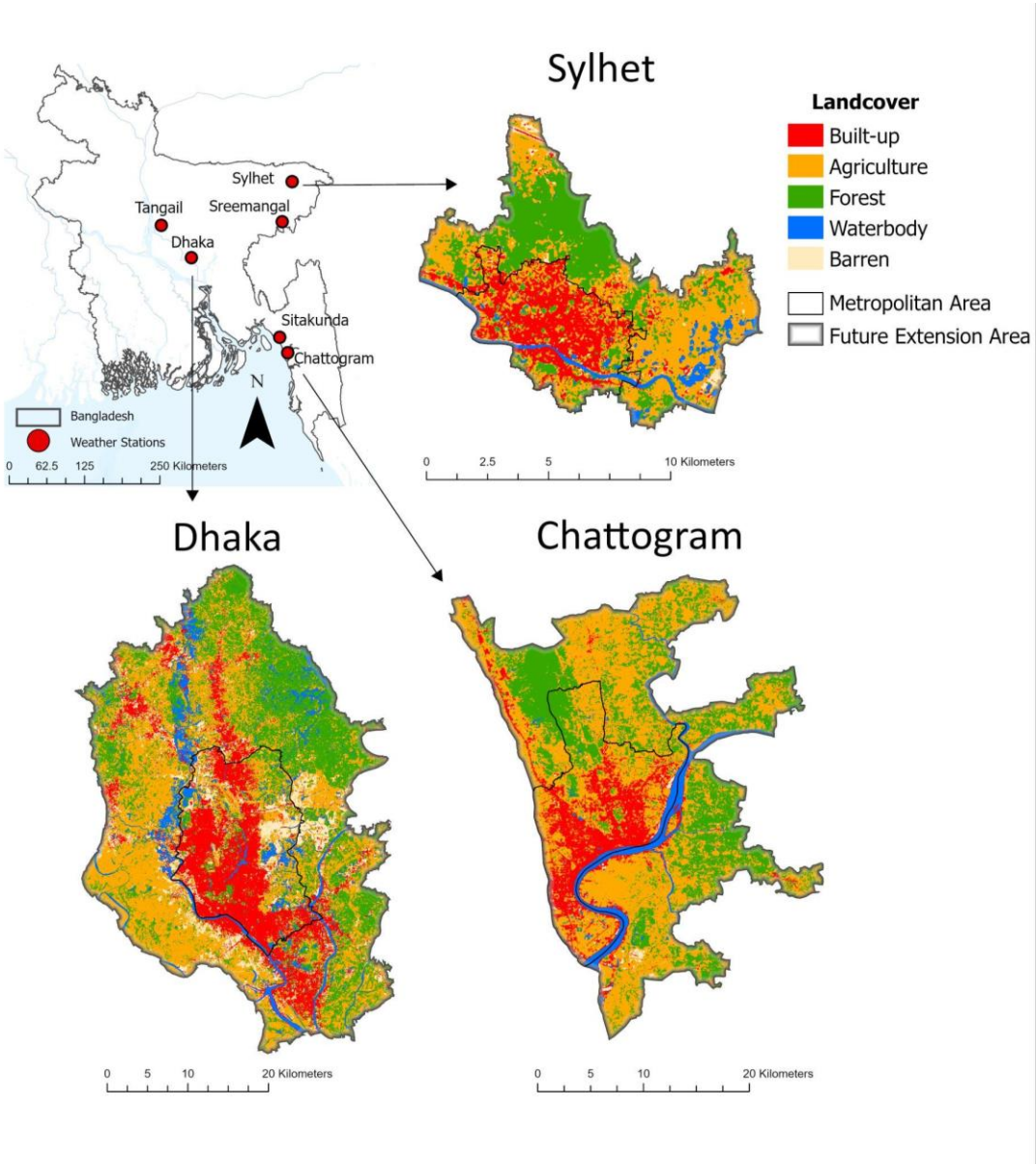


Figure 3.1: Location of observed weather stations along with the land use pattern in the existing metropolitan area and their proposed future extension area of Dhaka, Chattogram, and Sylhet.

3.2.2 UHI measurement

In this study, we analyze three datasets - in situ observational weather station data and satellite-derived LST from Landsat and MODIS. The in-situ weather station data (monthly maximum, minimum, and mean temperature and relative humidity observations) were collected from the Bangladesh Meteorological Department (BMD) from January 1988 to June 2023 (35.5 years) for six weather stations (Figure 3.1). To examine the AUHI, we compare the temperature differences between the urban core and the surrounding rural areas by selecting one weather station to be representative of each area. The main weather stations for Dhaka, Chattogram, and Sylhet were first selected and then their nearest weather stations with available atmospheric temperature data were chosen and located in the rural areas of Tangail, Sitakunda, and Sreemangal, respectively. Each rural station was carefully evaluated in Google Earth to assess its landscape. Stations were selected based on two primary criteria: a long, continuous record of weather data and a location with minimal urban footprint to ensure rural representativeness. While these stations are located in small villages, they are situated on the outskirts in sparsely developed areas, minimizing the influence of urbanization.

In addition to analyzing temperature differences, a humidity analysis was also conducted to better understand urban-rural atmospheric dynamics. For this, the same six meteorological stations in the three cities were considered, focusing on dew point temperature as the primary moisture variable due to the limited availability of additional data sources. Monthly average dew point temperatures were calculated, allowing for an assessment of humidity trends over the study period.

To comprehensively understand the differences in temperature dynamics between urban and rural areas, this study applies both a paired two-tailed *t*-test and the

Mann-Kendall trend test. The *t*-test is used to assess statistically significant differences in monthly mean temperatures between urban and rural day and night temperatures, while the Mann-Kendall test identifies temperature and dew point temperature trends over time. Together, these analyses reveal the influence of urban heat islands on local temperatures and moisture conditions and provide insights into the impacts of urbanization on climate variability. A p-value threshold of 0.05 was used for statistical significance in both tests, providing insights into the differential impacts of urbanization on temperature and humidity patterns.

To determine the SUHI, satellite derived mean LST was used in the pre-monsoon (March-May) summer period. The pre-monsoon summer period was chosen to assess SUHI intensity, as UHI effects are more prominent during this season due to clearer skies and lower humidities (Pandey et al., 2014; Shastri et al., 2017). Landsat data provides information for daytime LST and, therefore, represents only daytime SUHI. For Landsat data in Dhaka city, individual years of 2001, 2011, 2019, 2021, 2022, and 2023 were used. For Chattogram and Sylhet, three yearly composite images of 2001, 2011, and 2021 were needed due to cloud cover. We used the open-source code by Ermida et al. (2020) to derive the mean LST in Google Earth Engine (GEE) using freely available Landsat data at 30 meter spatial resolution. GEE is a cloud-based platform where users can easily process large datasets without having to download the data and are able to leverage the data processing on the cloud. In addition to the Landsat data, Terra MODIS Land Surface Temperature and Emissivity daily global data at 1 kilometer spatial resolution (MOD11A1 V6) was used to access the daytime and nighttime mean LST data again using GEE. Both day and night

scenes of MODIS mean LST temperature were incorporated to determine the daytime and nighttime SUHI intensity.

To assess the SUHI effect, we considered a comparison between the built-up (impervious) and non-built-up (permeable) areas within the present municipal boundaries of the cities and their anticipated expansion areas, as delineated by the municipal authorities, because urban administrative boundaries do not perfectly represent urban main built-up area (Meng et al., 2018). We utilized Landsat 5 and 8 satellite data with a spatial resolution of 30 meters to categorize the land surfaces of these three cities. We generated a three-year time composited image stack of 44 bands and employed a pixel-based Random Forest (RF) supervised classification using the GEE cloud computing platform. The land use was classified into five distinct classes: built-up, agricultural, forest, waterbodies, and barren/bare soil, as described in detail in the previous chapter that enabled the division between built-up and non-built-up land use. Using ArcGIS Pro, the mean LST data was segregated based on each land use type for the pre-monsoon summer period. This analysis aimed to uncover temperature variations across these land use categories and visualize the evaluation of the SUHI phenomenon over time.

3.3 Results

3.3.1 Weather Station Data

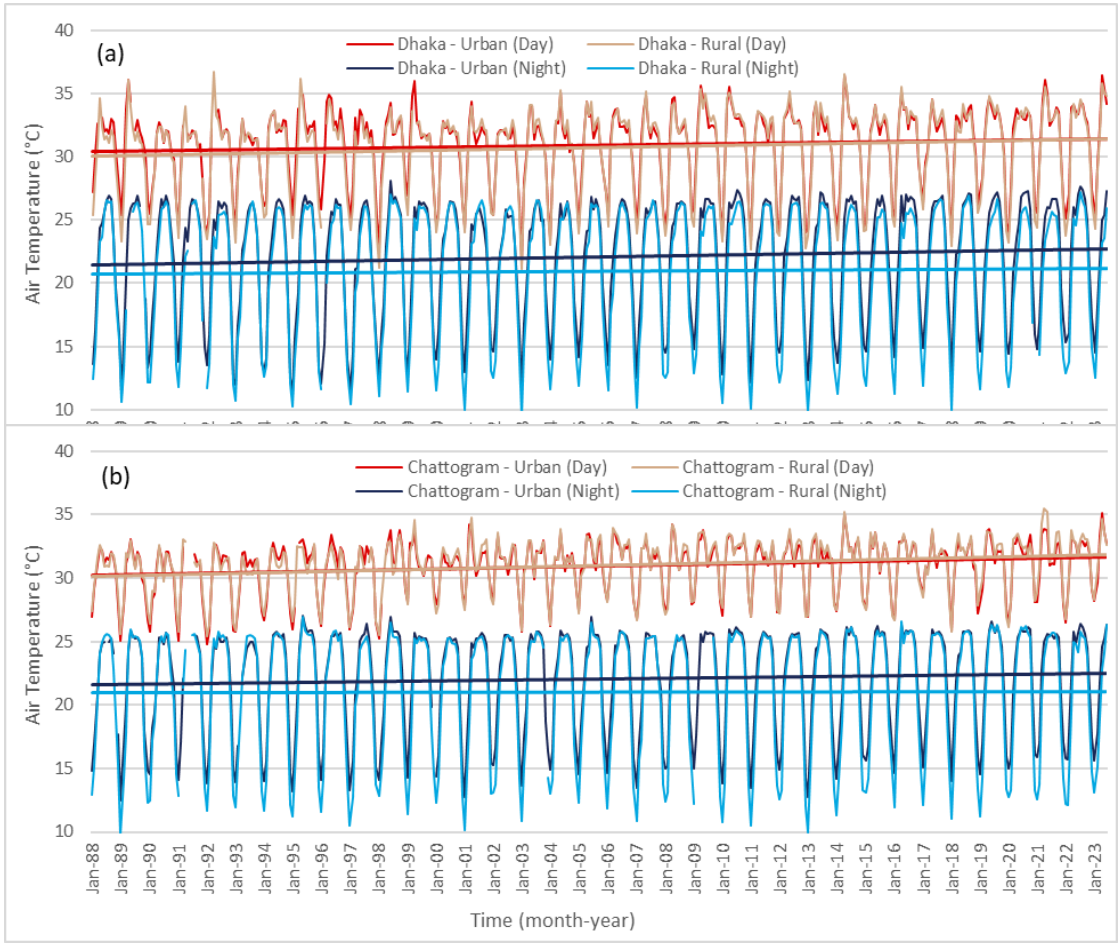
The daytime and nighttime air temperature observations in urban and rural areas in Dhaka, Chattogram, and Sylhet from 1988 to 2023 are presented in Figures 3.2a, 3.2b, and 3.2c, respectively. A linear trendline is also shown in Figure 3.2. The trend lines indicate an increase in daytime and nighttime air temperatures both in the

urban and rural areas for all three cities over the last 35.5 years. The average monthly daytime temperature in the three cities varied from 28.7°C to 30.4°C in 1988 and ranged between 30.0°C and 31.5°C in 2023. The rate of increase in monthly average daytime temperatures in the three cities during the study period varied between 0.03°C and 0.04°C per year. Dhaka's urban daytime temperature showed the greatest increase of 1.5°C.

The nighttime average monthly temperatures across Dhaka, Chattogram, and Sylhet reveal a clear urban warming trend over the past 35.5 years, with urban areas experiencing greater increases than their rural counterparts. In Dhaka, the urban nighttime temperature rose from approximately 21.3°C in 1988 to 22.6°C in 2023, at a rate of 0.04°C per year, while the rural area showed a more modest increase from 20.8°C to 21.3°C, indicating a slower warming rate of around 0.01°C per year. Similarly, Chattogram's urban nighttime temperature increased from 21.7°C to 22.6°C, with no significant change in its rural nighttime temperature. Sylhet displayed a pattern comparable to Dhaka, with an urban nighttime increase from 20.3°C to 21.6°C (0.04°C per year), while rural areas saw a modest increase from 19.1°C to 19.7°C, at a rate of 0.02°C per year.

The Mann-Kendall trend analysis reveals a statistically significant increasing trend in urban daytime and nighttime temperatures across all three cities, with Sylhet exhibiting the most pronounced trend for daytime (results in Table 3.1) and consistent increases in nighttime temperatures in urban Dhaka and Chattogram. Meanwhile, rural areas exhibit significant daytime trends but no significant nighttime trends, emphasizing the heightened influence of the urban heat island effect on urban night temperatures. The paired two-tailed *t*-test results indicate a significant difference

between the urban and rural day and night temperatures across all three cities, with very low p-values supporting this finding. The low p-values suggest that these differences are highly statistically significant, emphasizing the effects of urbanization on temperature patterns.


(a)
Dhaka - Urban (Day)
Dhaka - Rural (Day)
Dhaka - Urban (Night)
Dhaka - Rural (Night)
Air Temperature (°C)
40
35
30
25
20
15
10
(b)
Chattogram - Urban (Day)
Chattogram - Rural (Day)
Chattogram - Urban (Night)
Chattogram - Rural (Night)
Air Temperature (°C)
Jan-88
Jan-89
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
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Time (month-year)

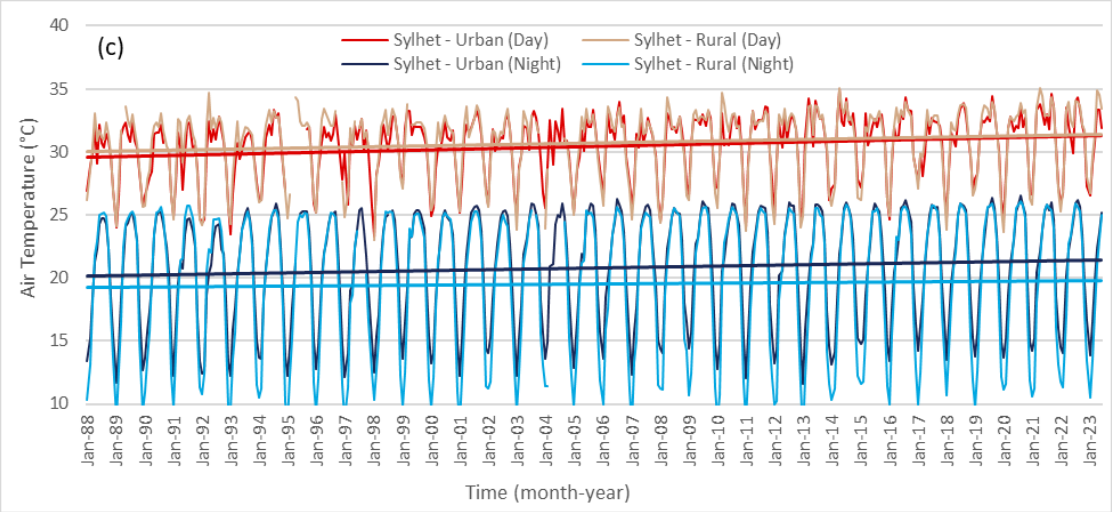

Figure 3.2: Variation in urban and rural daytime and nighttime air temperatures, including linear trendlines over the last 35.5 years in (a) Dhaka, (b) Chattogram, and (c) Sylhet.

Table 3.1: Mann-Kendall test results for day and night temperatures in urban and rural areas.

City	Time	Area	Trend	p-value
Dhaka	Day	Urban	increasing	0.0003
		Rural	increasing	3.9×10-6
	Night	Urban	increasing	0.0179
		Rural	no trend	0.7071
Chattogram	Day	Urban	increasing	1.15×10-5
		Rural	increasing	0.0001
	Night	Urban	increasing	0.0141
		Rural	no trend	0.2832
Sylhet	Day	Urban	increasing	5.62×10-7
		Rural	increasing	3.26×10-5
	Night	Urban	increasing	0.0139
		Rural	no trend	0.1552

The results of the Mann-Kendall trend analysis for the station pairs provide insights into the dew point temperature time series trends. For Dhaka's urban station, the analysis exhibits no trend, meaning there has been no significant change in its dew

point temperature over time, which is further corroborated by the lack of a consistent upward or downward pattern in the observations. Similarly, Dhaka's rural station shows no trend, with a non-significant p-value, confirming the stability of dew point temperature over the studied period. In contrast, Chattogram's urban station displays a statistically significant increasing trend (results in Table 3.2), indicating a gradual rise in dew point temperature, supported by the positive slope. Similarly, Chattogram's rural station shows a significant increasing trend, reflecting a noticeable increase in the dew point temperatures over time, with a slope of 0.0025. For Sylhet's urban, an increasing trend was found. Sylhet's rural, the strongest significant increasing trend is found, suggesting a consistent rise in dew point temperature. This indicates that Sylhet's rural station is experiencing one of the fastest rates of warming dew point temperatures.

Table 3.2: Mann-Kendall test results for Dew Point Temperature.

Station	Trend	p-value	Sen's Slope
Dhaka Urban	no trend	0.9986	-1.27×10-6
Dhaka Rural	no trend	0.6403	0.0004
Chattogram Urban	increasing	0.0444	0.0017
Chattogram Rural	increasing	0.0130	0.0025
Sylhet Urban	increasing	0.0301	0.0023
Sylhet Rural	increasing	0.0074	0.0028

The relative humidity observations were used to derive the dew point temperature at both urban and rural stations in each city. The dew point temperature time series for each city station pair did not vary significantly. Figure 3.3 illustrates the dew point temperatures for the Sylhet's urban and rural station, where it is apparent that the temperatures do not vary substantially between the two areas. However, we did find that the rural stations sometimes showed higher dew point

temperatures due to higher moisture content related to natural vegetation transpiring and water bodies evaporating observable in Figure 3.3 where the blue line (rural) falls above the red (urban).

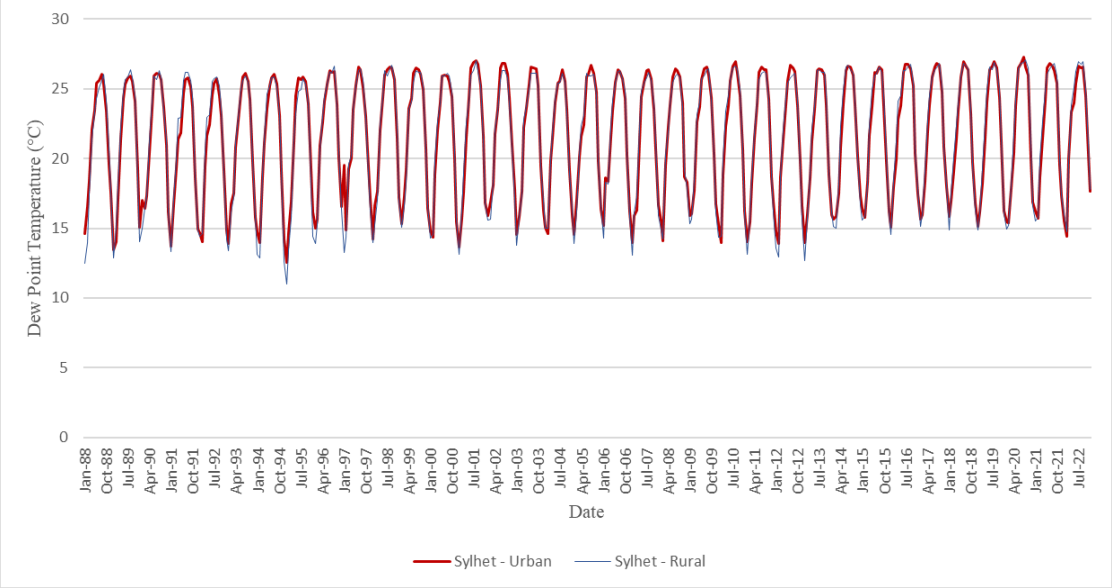

Figure 3.3: Dew point temperatures in Sylhet urban and rural stations.

Previous studies have shown that the urban heat island intensity reaches its peak on tranquil and cloudless nights (Santamouris, 2015). In this study, the nighttime temperatures show a greater AUHI compared to daytime temperatures with the nighttime AUHI rising 0.8°C for all three cities from 1988 to 2023. This result is consistent with the findings from published literature that nighttime AUHI is more prominent than daytime (Arnfield, 2003; Bohnenstengel et al., 2011; Chakraborty et al., 2017; Emilsson, 2021; Oke, 1987; Pandey et al., 2014; Ripley et al., 1996; Schmidlin, 1989; Sham, 1986; Tereshchenko & Filonov, 2001). The major cause for

AUHI nighttime temperatures is the altered energy balance (Oke, 1987; Rajagopalan et al., 2014). The urban environment disrupts the natural energy balance by increasing heat absorption and decreasing heat loss through factors like reduced vegetation, increased building density, and altered surface properties. This imbalance is more pronounced at night due to typically lower wind speeds, which reduce heat dispersion from urban surfaces, leading to heat accumulation and elevated nighttime temperatures in cities (National Weather Service, 2023; accessed from https://www.weather.gov/source/zhu/ZHU_Training_Page/winds/Wx_Terms/Flight_Environment.htm).

3.3.2 Satellite Data

3.3.2.1 Landsat

The temporal and spatial depiction of the LST for all land cover types for all three cities in the last two decades are shown in Figures 3.4 to 3.9. The temporal analysis for Dhaka reveals a notable trend, as displayed in Figure 3.3, of consistently elevated LST in the built-up areas, increasing significantly from 32.3°C in 2001 to 36.9°C in 2023. The rate of LST increase in built-up areas has surged to approximately 0.21°C per year, indicating a rapid warming trend. Barren land (mostly land under construction or sand-filled low-lying areas) exhibited the highest LST (35°C in 2001 to 37.3°C in 2023) among all land use categories, underlining the substantial influence of surface properties on local temperature dynamics. Barren and forest areas exhibited the smallest increase in LST over the same period except from 2022 to 2023. These non-built-up areas have experienced a comparatively mild temperature increase, with rates ranging from approximately 0.05 to 0.14°C per

year. An interesting LST jump occurred for all land cover types from 2022 to 2023 as the result of the heat waves the country experienced in 2023 (for a total of 62 days, spanning 24 days in April, 22 days in May, and 16 days in June) (Molla, 2023). As one example, Bangladesh's average monthly maximum temperature is normally around 30°C (86°F) with temperatures reaching 33°C (91°F) in April (World Bank, 2021). However, on 16 April 2023, the temperature in Dhaka soared to 40.6°C (105.1°F), marking the highest recorded temperature in 58 years, causing discomfort for residents for over a week due to the record temperatures, which were also compounded by high humidity (Molla, 2023).

Along with the temporal analysis, Figure 3.5 presents a spatial distribution of average pre-monsoon summer daytime LST across Dhaka during the same 22-year period, offering a geographical perspective of the changing temperatures and, more specifically, the growth of the urbanized areas of Dhaka over time. The spatial distribution of Dhaka's pre-monsoon daytime LST over time is displayed in Figure 3.5. In 2001, only the urbanized core in the center of the metropolitan area measured LSTs of 35°C to 40°C, while the surrounding areas had temperatures between 30°C to 35°C, and the adjacent urban periphery had LSTs below 30 °C. The built-up areas have increased throughout the city by 2023, and the previous non-urban areas in the periphery have transformed into urbanized areas, with much of the metropolitan area experiencing temperatures above 35 °C except the northeastern region, which still consists of vegetated areas. The spatial distribution of LST (as illustrated in Figure 4) provides compelling evidence of the sustained upward trend in LSTs over time and the alarming localized spots of temperature greater than 45 °C.

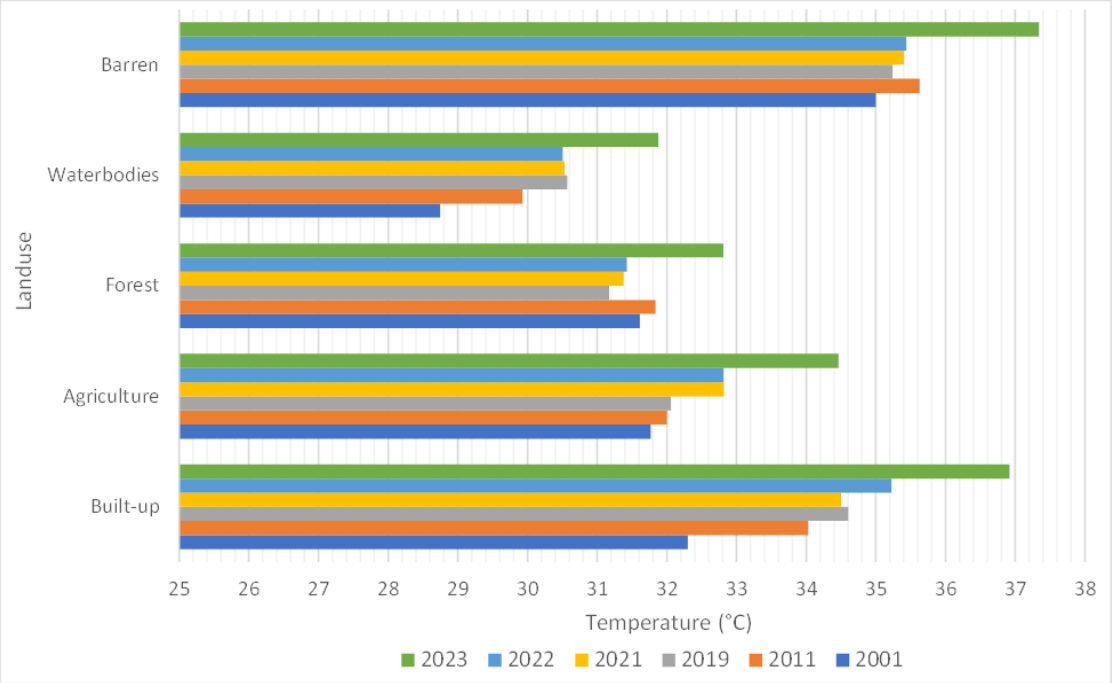

Figure 3.4: LST changes over time in Dhaka.

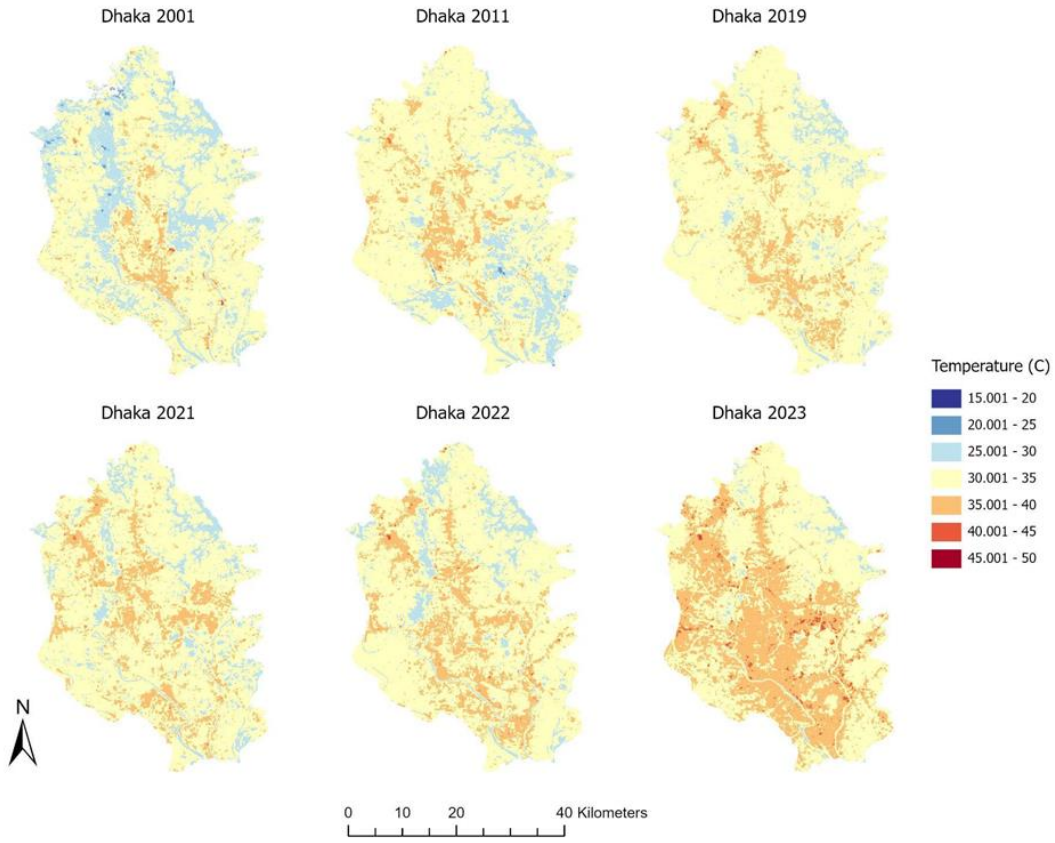

Figure 3.5: Spatial distribution of average pre-monsoon season daytime LST in Dhaka over the last 22 years.

Figure 3.6 provides the 20-year average pre-monsoon summer daytime Landsat-derived LST across Chattogram from 2001 to 2021. The Chattogram LSTs had a smaller increase over the 20-year period in comparison to Dhaka. The built-up, agriculture, and barren showed a temperature increase over time, while waterbodies remained rather stable and the forest land cover LST decreased. The decrease in forest land cover LST is contrary to an increase in forest area in the first decade as found in the land use change analysis explained in the previous chapter. Chakma et al. (2023)

study confirms our results reporting a 58% increase in forest cover from 1998 to 2018. The rate of LST rise in built-up areas stands at approximately 0.07°C per year over the past two decades. This rate is notably higher than the increase in non-built-up areas, where LST has risen much slower, ranging from approximately 0.00 to 0.01°C per year.

Figure 3.7 complements this temporal analysis by illustrating the spatial distribution of pre-monsoon summer daytime Landsat-derived LST across Chattogram for 2001, 2011, and 2021. The expansion of areas that experienced LST greater than 35 °C (areas colored orange) over the twenty-year period is noticeable as the urban core grew to its present extent. This urbanized growth is clearly evident by the warmer temperatures northward of the Karnaphuli River and to the northwest due to decreased vegetation with the increased industrialization in Sitakunda.

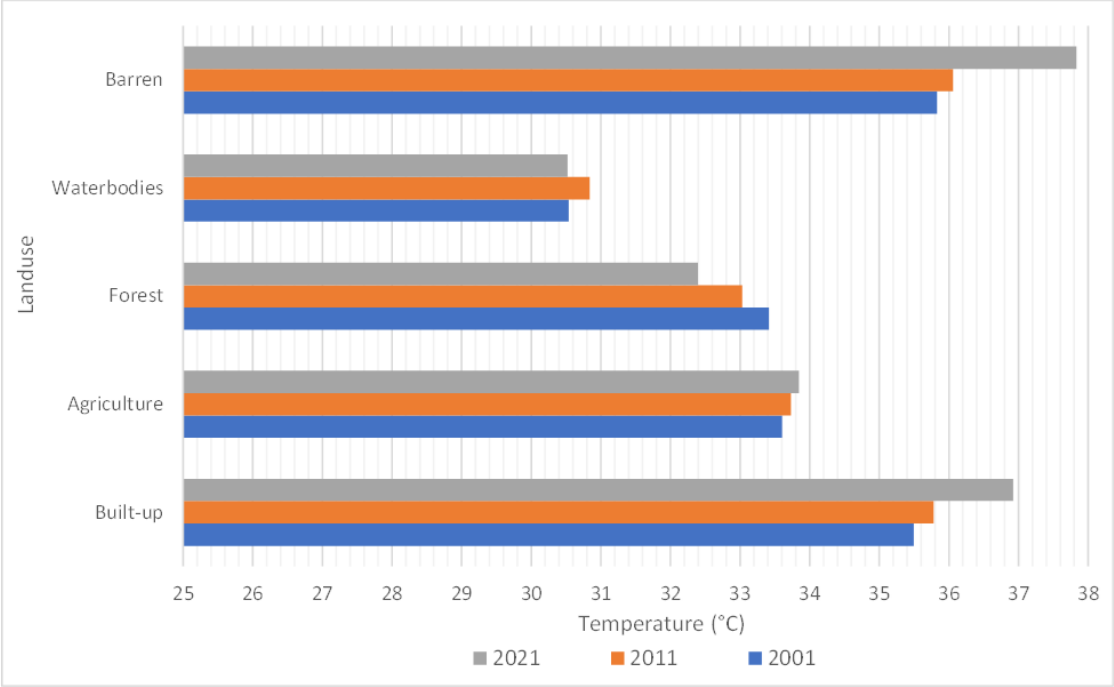

Figure 3.6: LST changes over time in Chattogram.

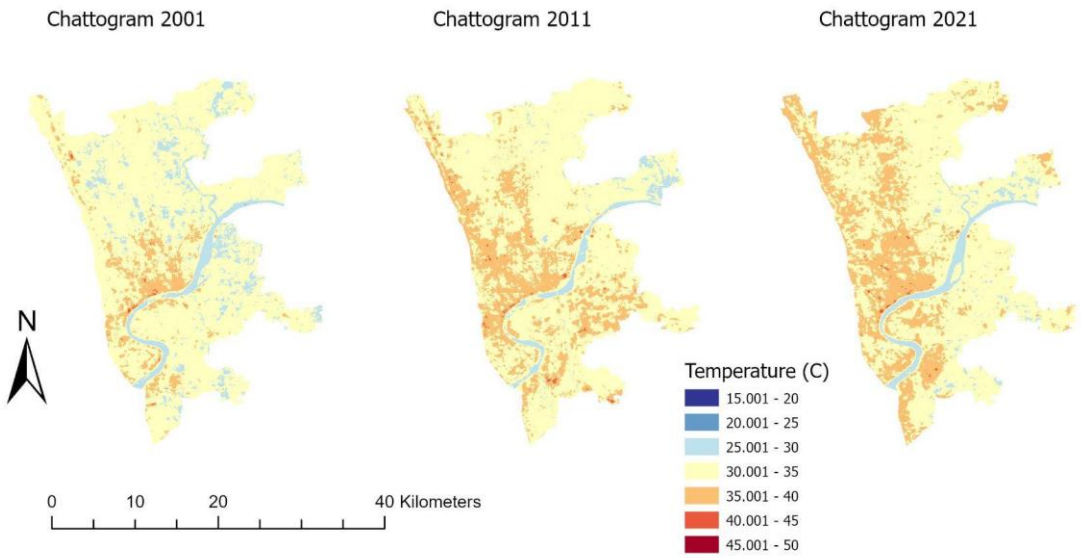

Figure 3.7: Spatial distribution of LST in Chattogram during the last two decades.

Figure 3.8 shows the temporal variation of LST in Sylhet, while Figure 3.9 presents the spatial distributions of LST over the 20-year time period. The rate of LST increase in built-up areas has been approximately 0.13 °C per year over the past two decades, which is higher than the rate of increase in non-built-up areas, ranging from approximately 0.07 to 0.08 °C per year. Both waterbodies and barren land increased nearly 2 degrees from 2001 to 2011, but then decreased in the last decade. Moreover, the spatial distribution of LST, as depicted in Figure 3.9, visually reinforces the observed increase in LST over time.

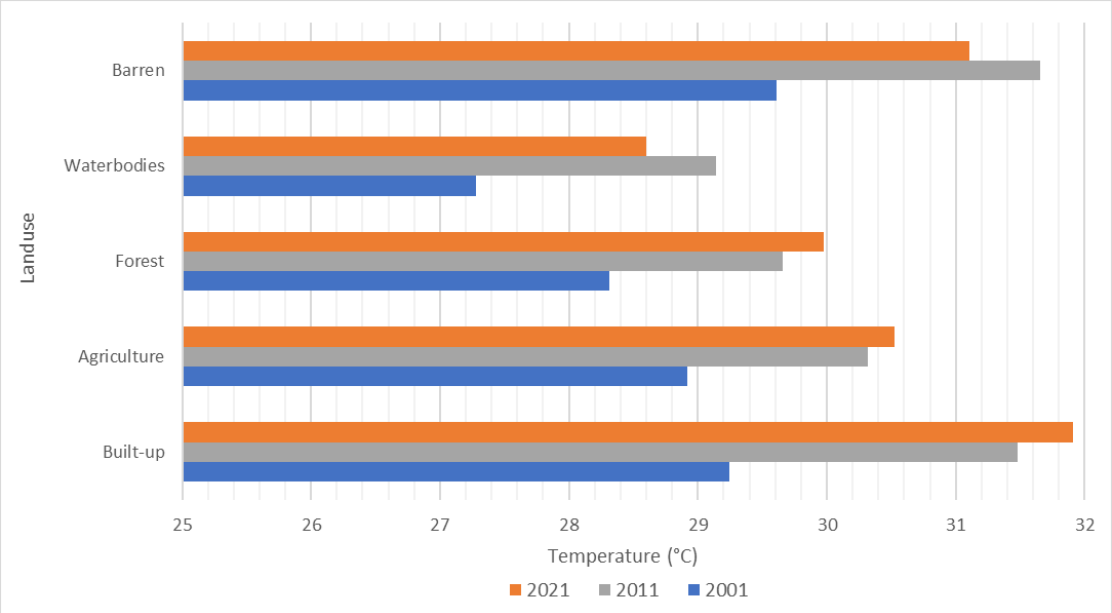

Figure 3.8: LST changes over time in Sylhet.

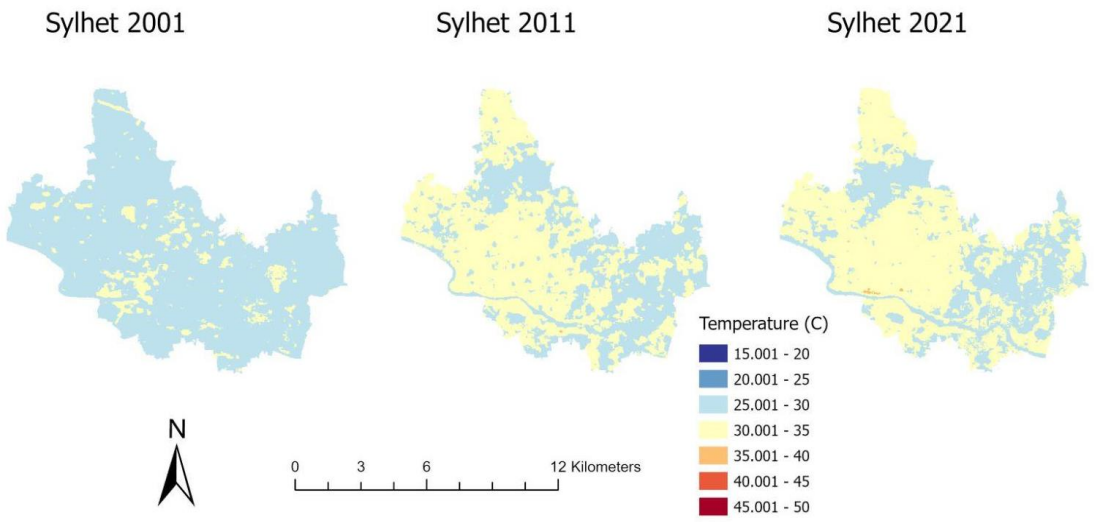

Figure 3.9: Spatial distribution of LST in Sylhet during the last two decades.

The Landsat-derived daytime SUHI results from this study are shown in Table 3.3, with all three cities experiencing an increase in SUHI from 2001 to 2023. The SUHI effect in Dhaka exhibited a noticeable escalation in intensity between 2001 and 2023. In 2001, the SUHI intensity stood at 1.6°C, and by 2023, it had surged to 3.9°C. This significant increase highlights the UHI's growing impact in the city, leading to elevated temperatures and associated environmental challenges. In Chattogram, the SUHI effect has shown a consistent upward trend and the greatest SUHI increase. In 2001, the SUHI intensity in Chattogram was measured at 3°C, while by 2021, it had risen to 4.7°C. This substantial increase in SUHI intensity underscores the urbanization and associated heat retention in Chattogram, which can have implications for the local climate, energy consumption, and human comfort. Sylhet has also experienced a discernible increase in SUHI intensity over the same period. In 2001, the SUHI intensity in Sylhet was relatively lower at 1.1°C, but by 2021, it had climbed

to 2.2°C. While the increase in Sylhet's SUHI intensity is relatively modest compared to Dhaka and Chattogram, it still reflects the expanding urban landscape and its potential influence on energy demands and overall urban sustainability.

Table 3.3: Landsat-derived daytime LST in study areas.

Land cover LST	Dhaka		Chattogram		Sylhet	
	2001	2023	2001	2021	2001	2021
Built-up Temperature (°C)	32.3	36.9	35.5	36.9	29.3	31.9
Non-built-up Temperature (°C)	30.7	33.0	32.5	32.2	28.2	29.7
Temperature difference/ SUHI (°C)	1.6	3.9	3.0	4.7	1.1	2.2

3.3.2.2 MODIS

The MODIS-derived daytime and nighttime pre-monsoon summer LST differences between built-up and non-built-up areas represent the SUHI in the three Bangladeshi cities over the past 20 years. The results are shown in Tables 3.2 and 3.3. For Dhaka and Sylhet, the daytime LST in built-up areas has increased by 1.3°C, whereas non-built-up areas showed a smaller increase of 0.8°C. Nighttime LST for Dhaka built-up increased by 1.9°C from 2001 to 2021 and non-built by 1.6°C. Chattogram nighttime LST increased by 1.1°C in built-up areas and non-built by 0.4°C from 2001 to 2021. Sylhet built-up and non-built-up areas had an increase in nighttime LST by 0.9°C.

The day and night SUHI for the three Bangladeshi cities nearly doubled from 2001 to 2021 except for daytime SUHI intensity in Chattogram with a slight decrease (0.2 ℃) and for nighttime SUHI intensity in Sylhet that showed no change over the

two decades. The greatest increase in SUHI intensity occurred in Sylhet's daytime SUHI intensity (increased by 0.6 ℃) and Chattogram's nighttime SUHI intensity (increased by 0.7 ℃). Both Dhaka and Chattogram nighttime SUHI increased over the 20 year time period. This notable escalation highlights the significance of understanding and mitigating the heat island effects.

Table 3.4: MODIS-derived daytime LST in study areas.

LST in different land use	Dhaka		Chattogram		Sylhet	
	2001	2021	2001	2021	2001	2021
Built-up temperature (°C)	31.5	32.8	33.3	33.0	30.5	31.8
Non-built-up temperature (°C)	31.0	31.8	31.8	31.7	30.2	31.0
Temperature difference / SUHI (°C)	0.5	1.0	1.5	1.3	0.3	0.8

Table 3.5: MODIS-derived nighttime LST in study areas.

LST in different land use	Dhaka		Chattogram		Sylhet	
	2001	2021	2001	2021	2001	2021
Built-up temperature (°C)	21.2	23.1	22.9	24.0	21.8	22.7
Non-built-up temperature (°C)	20.9	22.5	22.1	22.5	20.9	21.8
Temperature difference / SUHI (°C)	0.3	0.6	0.8	1.5	0.9	0.9

3.4 Discussion

Table 3.6 provides a summary of our findings and where appropriate a comparison with two other studies investigating satellite-derived LST in Bangladesh (Chakroborty and Lee 2019, Dewan et al. 2021). The daytime AUHI intensity over the 35.5 year period differs with an increase for Dhaka, a small consistent decrease for Chattogram, and intensities vary for Sylhet. However, the nighttime AUHI intensities all increase over the observational record from 0.6°C to 3°C, with the smallest and

largest intensity change for Sylhet during summer and winter, respectively as shown in Table 3.6. Our findings show that the urban area alters the energy balance with its materials absorbing and retaining more heat. Urban activities release additional heat with automobile exhaust and air conditioning, and the density of buildings trap heat and alter air circulation, all causing daytime air temperature trends to be erratic, while nighttime air temperature trends tend to show a steady increase. The energy absorbed by the impervious land surfaces during the day is continually emitted at night, so temperatures do not fall as with natural, rural surfaces, keeping nighttime urban areas warmer. Although this analysis only compares three urban locations with three rural stations, the disparity in nighttime air temperature trends between urban and rural locations highlights the UHI effect and the impact of urban development on the local climate of Dhaka, Chattogram, and Sylhet cities in Bangladesh. This result is consistent with the other studies documenting the increase in nighttime temperature over time.

Satellite data analysis provides the next step to gain a comprehensive look at the spatial patterns of the UHI over time. Our study analyzed both Landsat and MODIS derived LST for the pre-monsoon summer season. We found Landsat-derived average pre-monsoon summer daytime SUHI intensities of 1.7°C, 3°C, and 3.6℃ for Sylhet, Dhaka, and Chattogram, respectively (Table 3.4). The Landsat-derived mean temperature increase in daytime SUHI values were higher than the values found from MODIS derived LST analysis. The reason behind this variation is associated with the spatial resolution of the satellite image, as Landsat has a higher resolution and is able to capture more details of the heterogeneous urban environment than MODIS.

Two previous studies (Dewan et al., 2021; Chakraborty and Lee, 2019) have examined daytime and nighttime SUHI computed from MODIS for approximately the same time period of the last 20 years, focusing on annual to seasonal time scales. Chakraborty and Lee (2019) found that annual average SUHI intensities increased 0.33℃ (Chattogram nighttime) to 1.60℃ (Dhaka daytime), with the daytime SUHI intensities increasing more than the nighttime and Dhaka having the largest increase. Dewan et al (2021) found a similar pattern for annual average SUHI intensity changes over the last 19 years, with daytime SUHI intensity increasing larger than nighttime intensities even though the SUHI intensities are different. Dewan et al. (2021) reported the mean temperature increase in daytime SUHI values were 0.98°C, 0.48°C, and 0.38°C for Dhaka, Chattogram, and Sylhet, respectively, while our study found 0.5°C, - 0.2°C, 0.5°C respectively from MODIS data. Considering the mean temperature increase in nighttime SUHI values from MODIS data, our study found values of 0.3°C, 0.7°C, and 0°C for Dhaka, Chattogram, and Sylhet, while Dewan et al. (2021) reported 0.2°C, 0.5°C, and 0.3°C increase in SUHI intensity respectively. The variation between the UHI intensity values reported by Dewan et al. (2021) (2000-2019) and the values found in this study (2001-2021) is likely due to slightly different time frame analyzed, our analysis of pre-monsoon monthly average temperature versus average annual temperature analysis by Dewan et al. (2021), and the different way Dewan et al.'s (2021) study defined urban versus non-urban/rural areas by the city municipal boundary and our study which explicitly used the landuse classification type to delineate the impervious and permeable land use.

Chakraborty and Lee (2019) examined the seasonal SUHI intensities from MODIS data over the 20-year period (2000-2017 for Terra and 2002-2017 for Aqua)

and found the summer (June-August) SUHI intensities increased by 1.3°C to 2.2°C, with Chattogram having the largest increase. Our pre-monsoon summer (March-May) daytime SUHI results from MODIS data are similar, although our SUHI intensities increase less, ranging from 0.5°C to 1.2°C because of the focus on the pre-monsoon summer period. The nighttime SUHI intensity change over the last 20 years is quite different. Chakraborty and Lee (2019) found the average nighttime summer SUHI intensity to be 0.1°C, -0.1°C, and 0.2°C in Dhaka, Chattogram, and Sylhet, respectively. Comparing these with our study, the values were found to be 0.4°C, 0.9°C, and 0.9°C for Dhaka, Chattogram, and Sylhet, respectively, for pre-monsoon summer. Our SUHI intensities are larger than those reported by Chakraborty and Lee (2019) and do not follow the same pattern. The differences in the SUHI intensities between our study and Chakraborty and Lee (2019) are attributed to the different summer months used for data analysis and the definition of urban versus non-urban areas to calculate the UHI intensities. Our pre-monsoon summer months are typically characterized by clearer skies with hot temperature and high humidity compared to the peak summer months which experience monsoon rainy season. Chakraborty and Lee (2019) also investigated the winter SUHI. They found the SUHI intensities increased over the 20-year period for both daytime and nighttime, with nighttime showing a larger increase in comparison to daytime except for Chattogram. Our study did not examine the winter season with a focus on the months with the highest temperatures.

Our findings plus those from the other two studies indicate that both daytime and nighttime Landsat and MODIS derived-LST rose faster in built-up areas compared to their non-built-up counterparts from 2001 to 2021 except Chattogram pre-monsoon nighttime temperature. The increasing LST differences point to the SUHI effect

highlighting the influence of urbanization, infrastructure development, and human activities on local climate conditions.

Our results from the *t*-test and Mann-Kendall trend analysis highlight significant differences between urban and rural temperature patterns in AUHI due to urbanization. Both day and night temperatures in urban areas are significantly higher than those in rural settings across Dhaka, Chattogram, and Sylhet, as confirmed by the *t*-test. The Mann-Kendall trend test further supports these findings, showing increasing trends in urban temperatures, particularly at night, which is characteristic of the UHI effect. Although humidity trends are increasing in Bangladesh (Fattah et al., 2023 reported an increasing rate of 0.083–0.53% per year in summer), dew point temperatures exhibit no significant long-term trends. This condition may be due to localized factors such as urban heat and land use changes that affect moisture retention and distribution (Fattah et al., 2023; Mortuza et al., 2014). Our study indicates that while dew point temperature is increasing, the lack of significant trends in temperature suggests a complex interaction between urbanization and local climatic conditions (Mortuza et al., 2014). Monitoring humidity alongside temperature is crucial due to their combined impact on human health.

Table 3.6: Comparison of findings on UHI from different literature on the study areas.

Publication	Data Type	Source of Data	Study Period	Data Differentiation	Study Areas[†]	Annual Average Daytime	Annual Average Nighttime	Summer[¥] /Pre-monsoon[§] Daytime	Summer[¥]/ Pre-monsoon[§] Nighttime	Winter[ƒ] Daytime	Winter[ƒ] Nighttime	Mean temperature increases in study period: Daytime	Mean temperature increases in study period: Nighttime	Annual Daytime	Annual Nighttime
						Surface Urban Heat Island Intensity (SHUI) (°C)								SUHII Trend (°C/yr)	
Chakraborty and Lee (2019)	LST	MODIS Terra MODIS Aqua	2000 – 2017 2002 - 2017	Urban/non-urban	Dhaka Urban Cluster	1.60	1.04	2.03	0.10	1.21	1.47	---	---	---	---
					Chattogram Urban Cluster	1.41	0.33	2.17	-0.09	1.16	0.48	---	---	---	---
					Sylhet Urban Cluster	0.68	0.59	1.28	0.25	0.25	0.75	---	---	---	---
Dewan et al. (2021)	LST	MODIS Terra	2000 - 2019	Urban/Rural	Dhaka City	2.74	1.57	---	---	---	---	0.98	0.23	0.062	0.012
					Chattogram City	1.92	1.90	---	---	---	---	0.48	0.52	0.046	0.007
					Sylhet City	1.10	0.16	---	---	---	---	0.38	0.34	0.017	0.015
This study	LST	MODIS Terra	2001 - 2021	Built-up vs non-built-up	Dhaka City	---	---	0.8*	0.4*	---	---	0.5	0.3	---	---
					Chattogram City	---	---	1.2[¤]	0.9[¤]	---	---	-0.2	0.7	---	---
					Sylhet City	---	---	0.5[¤]	0.9[¤]	---	---	0.5	0	---	---
		Landsat	2001 - 2023	Built-up vs non-built-up	Dhaka City	---	---	3*	---	---	---	2.3	---	---	---
			2001 - 2021		Chattogram City	---	---	3.6[¤]	---	---	---	1.7	---	---	---
			2001 - 2021		Sylhet City	---	---	1.7[¤]	---	---	---	1.1	---	---	---
						Atmospheric Urban Heat Island Intensity (AHUI) (°C)								AUHII Trend (°C/yr)	
	Air temp.	Weather station	Jan 1988 - June 2023	Urban vs Rural	Dhaka City	0.2	1.2	0.3	1.6	0.8	2	-0.3	0.8	-0.007	0.022
					Chattogram City	-0.1	1.1	-0.1	0.8	-0.1	2.4	0	0.8	0	0.023
					Sylhet City	-0.3	1.3	-0.9	0.6	0.3	3	0	0.8	0	0.022

Notes: [†]Chakraborty and Lee (2019) also studied 14 other urban clusters in Bangladesh and numerous urban clusters around the world. Dewan et al. (2021) also studied Khulna and Rajshahi cities.
[¥]June, July, and August were considered summer months by Chakraborty and Lee (2019).
[§]March, April, and May were considered pre-monsoon summer months in this study.
[ƒ]December, January and February were considered winter months by Chakraborty and Lee (2019) and this study.
*Based on pre-monsoon data from 2001, 2011, 2019, 2021, 2022, and 2023.
[¤]Based on pre-monsoon data from 2001, 2011, and 2021.

3.5 Conclusion

Urban areas worldwide are increasingly experiencing the adverse effects of the Urban Heat Island (UHI) phenomenon, driven by land-use changes, vegetation loss, and heightened heat production from human activities. Rapid, often unplanned urbanization in developing countries has led to extensive land conversion, with green spaces and water bodies replaced by built infrastructure to meet the demands of a growing urban population. This significant shift from permeable to impervious surfaces—such as dark infrastructure and pavements that absorb and retain more heat—has substantially contributed to rising land surface temperatures (LST), with the highest LST observed in barren and built-up areas. If these temperature trends continue, they pose even greater risks to environmental health and human well-being. Understanding these LST variations is crucial for fostering sustainable development and building resilience in rapidly urbanizing regions.

Over the past 20 years, Bangladesh has undergone significant transformations, leading to the development of UHI where pre-monsoon summer LST have reached extreme levels. For urban and environmental planners, it's crucial to have detailed information on the spatiotemporal pattern of UHI intensities as it identifies specific areas where heat management interventions would be most impactful. A few studies have examined the SUHI intensities over large cities in Bangladesh, but none have investigated the AUHI intensities in Bangladesh, nor documented both the AUHI and SUHI intensities together. In this study, we examined the AUHI and SUHI intensities in the three large Bangladesh cities - Dhaka, Chattogram, and Sylhet. The AUHI intensities were measured using 35.5 years of air temperature observations at a weather station located in the urban core and a rural setting. An additional novelty conducted in this study is the integration of atmospheric moisture with temperature

time series analysis to study the UHI in a tropical climate as Bangladesh. Studying atmospheric moisture content alongside temperature is essential for understanding human heat comfort because both factors together determine how we perceive and manage heat.

The temporal analysis of the AUHI intensity involved examining 35.5 years of urban and rural paired time series for each city, utilizing trendlines and statistical significance testing to evaluate the long-term patterns. The analysis revealed that urban and rural temperatures are statistically different, with urban areas consistently exhibiting higher temperatures. The results indicate that the nighttime AUHI is more pronounced than the daytime AUHI, with a continuous increase in nighttime air temperatures observed across all three study areas, highlighting the persistent impact of urbanization on nighttime warming. The *t*-test results demonstrate significant differences in daytime and nighttime urban and rural temperatures, and the Mann-Kendall analysis shows distinct increasing trends in urban areas. Similarly, the analysis of dew point temperatures revealed significant increasing trends in Chattogram and Sylhet for both urban and rural areas, while Dhaka exhibited no significant trend, indicating localized variations in atmospheric moisture dynamics influenced by urbanization.

Along with a temporal analysis of the AUHI, we conducted a spatial look at the UHI using satellite data. Instead of using the traditional city boundaries to define the UHI, we compared the temperature difference between impervious and permeable land surfaces derived from the land use classification in Bangladesh, which has a heterogeneous land use pattern. This definition of built-up and non built-up areas has not previously been done and defines more explicitly the effects of urbanization. Both

MODIS and Landsat satellite data over 20 years were utilized, where MODIS data provided the daytime and nighttime LST of the study areas, and Landsat data allowed for daytime LST at a higher spatial resolution. The pre-monsoon summer period was selected for this study because the intensity of SUHI is particularly strong in the dry months, which also coincide with the highest air temperatures in the study area. The MODIS derived LST results showed that Dhaka and Sylhet had the highest increase in daytime SUHI intensity of 0.5°C. Using the Landsat derived LST, Dhaka experienced the largest increase in daytime SUHI intensity of 2.3°C. The SUHI variation between the two satellite datasets is most likely due to the difference in the spatial resolution in the satellite data where Landsat (30-meter) has finer resolution compared to MODIS (1-kilometer), incorporating more details of the study area. For the nighttime SUHI intensity, Chattogram showed the largest increase of 0.7°C in SUHI intensity compared to the other two cities.

Considering the spatial distribution of LST, the urban core area with intense built-up areas, observed the highest LST. The green vegetated areas and the water bodies had lower LST as these land surfaces work as a cooling agent in any urban environment, underscoring the importance of permeable areas in a city in order to combat the increased heat of the built environment. Converting barren areas to parks and other green recreational facilities (with the purpose of reducing heat absorption and increasing cooling) would be an effective policy to combat UHI. In 2021, Dhaka had a significant amount of barren land (about 9% of the area), whereas Chattogram had only 1.08% and Sylhet had 2.28% of the total land area as barren.

The escalating UHI intensities, both SUHI and AUHI, across major cities in Bangladesh emphasize the pressing need for urban planning and climate resilience

strategies to address the challenges posed by urban heat islands. Mitigation strategy measures include the expansion of green spaces, increased vegetation, and the development of heat-resilient infrastructure to combat the adverse effects of rising temperatures in urban environments with a detailed analysis of Bangladesh's planning and urban strategies discussed in the following chapter. These strategies help cities develop sustainable urban planning approaches to mitigate heat-related challenges, alleviate heat stress, improve air quality, and enhance overall urban livability.

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Chapter 4

URBAN HEAT ISLAND MITIGATION STRATEGIES AND RECOMMENDATIONS FOR THREE MAJOR CITIES IN BANGLADESH

4.1 Introduction

Urban Heat Island (UHI) poses a significant challenge to sustainable development and livability of cities, particularly in rapidly urbanizing countries like Bangladesh. The urban landscape of Bangladesh, specifically its major cities of Dhaka, Chattogram, and Sylhet face pressing challenges associated with the UHI. As these cities continue to expand, so does the intensity of UHI. The proliferation of concrete structures, vehicular emissions, reduced green spaces, and environmental degradation exacerbate UHI intensity and pose significant risks to public health, energy consumption, and overall urban livability.

Dhaka, as the capital and mega city of Bangladesh, serves as the economic, political, and cultural hub of the nation. Its rapid urbanization has led to severe environmental degradation, with UHI emerging as a significant concern. Chattogram, the country's second-largest city, and a major seaport, faces similar challenges due to its dense urban development. Sylhet, nestled amidst picturesque hilly landscapes of tea gardens, also grapples with the UHI as it undergoes rapid urban expansion.

To combat the challenges posed by UHI, urban planners and policymakers have turned to development plans as key instruments for guiding development and implementing UHI mitigation measures. Previous research has explored various measures for mitigating the UHI effect, but those have seldom examined the policies

implemented by municipal development authorities to address UHI impacts. This gap highlights the need for a comprehensive review of local government initiatives, development plans and policies, and their effectiveness in combating UHI, including urban planning regulations, green infrastructure projects, and community engagement programs designed to reduce heat retention and promote sustainable urban cooling. This chapter undertakes a review of the strategies, proposals, and policies that directly or indirectly address the UHI issues in the most recent development plans of Dhaka, Chattogram, and Sylhet cities in Bangladesh. This chapter describes the measures each city has been able to accomplish to mitigate the UHI, identifies the gaps and limitations of these development plans in addressing the UHI issue, and provides recommendations for improvements.

Furthermore, this chapter provides a synthesis of best practices and innovative approaches observed in other global urban contexts, which could be adapted and integrated into the development plans of Dhaka, Chattogram, and Sylhet. Drawing upon insights from international case studies and expert recommendations (as found in existing literature), this synthesis offers actionable strategies tailored to the socio-economic and environmental context of Bangladesh. Ultimately, the findings of this review aim to inform urban planning practitioners, policymakers, and stakeholders about the importance of integrating UHI mitigation measures into development plans, thereby fostering more resilient, sustainable, and livable cities in Bangladesh.

4.2 Existing Development Plans

The municipal authorities are responsible for preparing future development plans and are accountable for acting on the proposed policies. A development plan is a policy guideline to direct future growth and development of a city. The city's future

development plans are designed after reviewing past plans and studying the city's present socio-economic and physical conditions. The existing and proposed development plans of the Dhaka, Chattogram, and Sylhet cities relevant to the issue of UHI were reviewed. The summaries are presented in the following sections.

4.2.1 Dhaka

4.2.1.1 Overview of Plans

Dhaka has formulated multiple development plans over the years, with the most recent spanning from the mid-1990s to 2035. A detailed review of these plans is provided in the following sections.

Structure Plan (published in 2016 for the time period of 2016-2035), referred to as the Dhaka Structure Plan (DSP) in this chapter, is a policy document that sets a long-term strategy for the future pattern and direction of coordinated urban development and serves as the guideline for subsequent local level plans. It is the highest-level spatial policy guideline for the Dhaka Metropolitan Region (DMR). It provides a framework within which more detailed plans and decisions can be made, indicating preferred areas for growth, types of development, infrastructure needs, and environmental considerations. The plan highlights strategic goals and objectives rather than prescribing detailed actions or regulations.

Urban Area Plan (published in 1997 for the time period of 1995-2005), referred to as the Dhaka Urban Area Plan (DUAP) in this chapter, is the policy document that provides strategies for the development of the urban area over a 10 year period. It also defines the area of proposed development during the plan period. This

plan has not been updated since published in 1997 and did not address the UHI issue in any significant way.

Detailed Area Plan (published in 2022 for the time period of 2022-2035), referred to as the Dhaka Detailed Area Plan (DDAP) in this chapter, is the most recent policy document that provides detailed planning proposals for specific sub-areas to be compliant with the Structure Plan and the Urban Area Plan. It was prepared with the current changing urban context in mind and updated with area-specific guidelines of various strategies, policies, and plans. This plan was structured in such a way that future planning or development decisions can be made according to the character and needs of the local areas.

4.2.1.2 Planning Regions

In the DSP, the entire DMR is divided into six main planning regions (referred to as MPRs in this chapter) by administrative boundaries, as shown in Figure 4.1. Subsequently, under the DDAP, these six regions were further subdivided into 75 relatively small sub-areas to facilitate the preparation of detailed planning and policy recommendations. A summary of the land area of the six MPRs is presented in Table 4.1.

Table 4.1: Summary of six main planning regions in Dhaka Metropolitan Region.

MPR	MPR Name	Total Area (Acre)
MPR 01	Dhaka Central Region (Dhaka North City Corporation (DNCC) and Dhaka South City Corporation (DSCC) Area)	75,849
MPR 02	Northern Region (Gazipur Area)	90,004
MPR 03	Western Region (Savar Area)	61,835

MPR	MPR Name	Total Area (Acre)
MPR 04	Southern Region (Narayanganj Area)	53,263
MPR 05	Eastern Region (Rupganj-Kaliganj Area)	54,058
MPR 06	South-Western Region (Keraniganj Area)	42,550

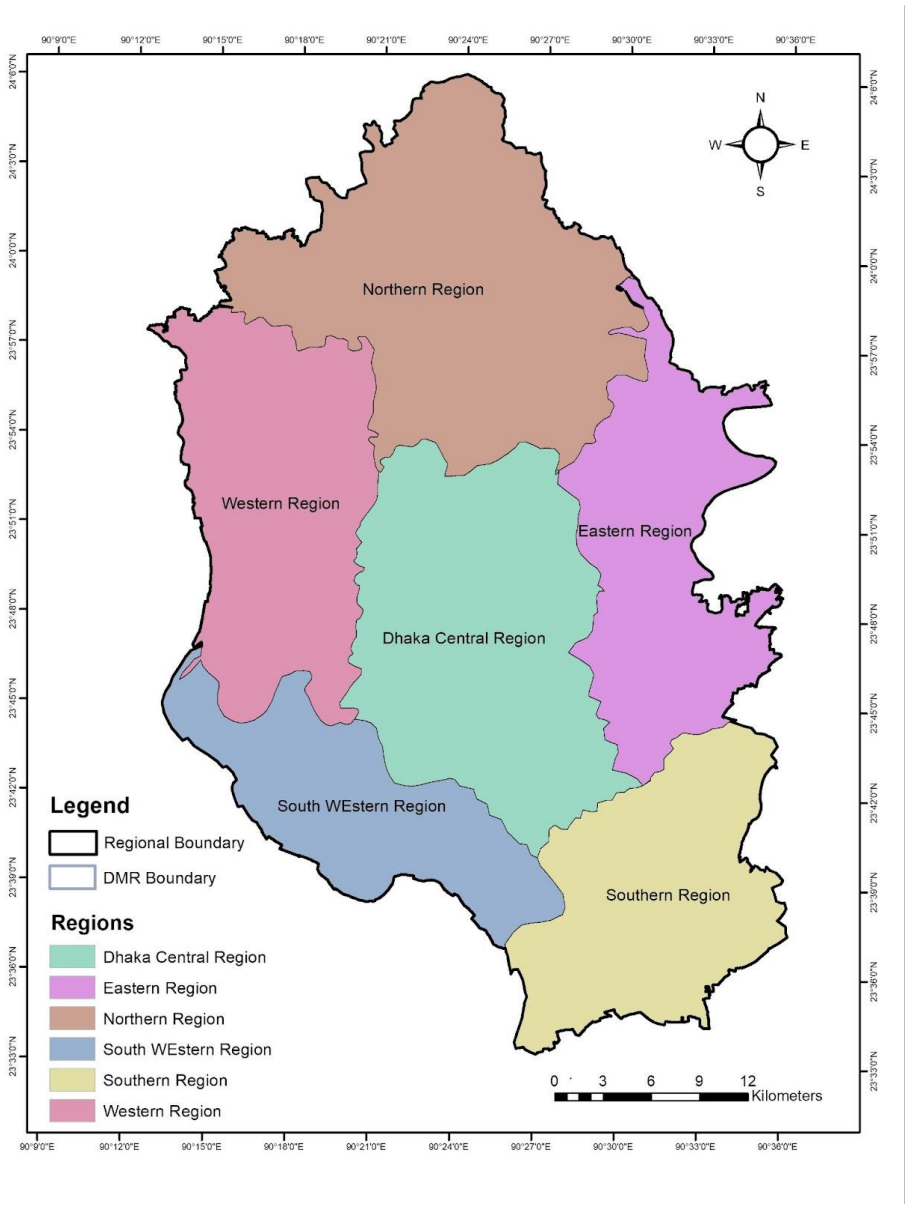

Figure 4.1: Six planning regions of Dhaka Metropolitan Region as presented in RAJUK (2016).

4.2.1.3 Climate Change Impact and UHI

Climate change is having a significant impact on Dhaka. The DSP included a discussion on the environmental issues aggravated by the impacts of climate change, such as temperature variation, erratic rainfall, flood and water logging, stronger and more frequent cyclones (Rojas, 2021), and climate-induced health outbreaks (increased vector-borne diseases like malaria, dengue fever; water-borne diseases like cholera, leptospirosis; respiratory illnesses like asthma and allergies; heat-related illnesses like heatstroke, dehydration, and heat exhaustion). The DSP report indicates summer temperatures in Dhaka range from 40°C to 43°C, peaking in April, sometimes exceeding 43°C with increasing maximum and minimum temperatures resulting in hotter summers. Over the past century, Dhaka's average temperature rose by 0.5°C, projected to increase by another 1.5 to 2 degrees in the next 50 years. The metropolitan area averages 2°C hotter than suburban zones, creating a heat island effect. Urban open space loss from urban expansion and densification traps heat, limits evaporative cooling, and contributes to Dhaka's annual temperature rise (RAJUK 2016).

4.2.1.4 Policies Directly Addressing UHI

The DDAP includes several policies directly addressing the UHI issue in Dhaka city (RAJUK 2022a). These policies mainly focus on tree planting, green plot ratio, green networks, preservation of green spaces and water bodies, and applying density zoning. Each of these policies is described below.

Tree planting is one major priority emphasized in the DDAP policy. The report indicates that all of the elements (asphalt and concrete, dark roofs, metal, and paved surfaces) that contribute to the increase in heat in building construction must be

eliminated, and to reduce heat, the building construction regulations must include the planting of trees in the construction of any type of structure installation. Planting trees on house roofs are also encouraged by providing a 10% household tax rebate. Under the Private Residential Land Development Rules, residential land development is given priority if the project includes planting trees, especially in areas where the impact of the UHI is high specifically in the urban core like Motijheel.

Just as with building construction, the DDAP requires tree planting for the construction of any type of road. The policy specifically indicates guidelines on urban lifelines must be followed when planting trees, for example, to avoid interference with infrastructure, allow clearance for roads and pathways, and ensure safety during storms. Here, urban lifelines refer to the essential systems and infrastructure that support the daily functioning and sustainability of urban areas. Urban lifelines include constructed utilities (such as water supply, sewage and waste management, electricity, gas, and other utilities), transportation systems (network of roads, highways, bridges, public transit systems (buses, subways, trams), railways, airports, and ports), telecommunication systems (telephone networks, internet services, satellite communications, and broadcast services), and critical facilities (hospitals, schools, emergency services (fire stations, police stations), government buildings, and shelters).

To promote greenery and sustainable development in urban environments, the DDAP policy has developed the concept of the Green Plot Ratio (GnPR) in building construction and urban planning. GnPR measures the ratio of the vegetated area (green roofs, vertical gardens, and ground-level vegetation) on a site to the total site area (total horizontal area of the site). Dhaka municipal planning authorities often set minimum GnPR requirements for new developments, renovations, or major site

improvements. Some regions also offer incentives, such as tax breaks or additional floor area allowances, for developments that exceed the minimum GnPR requirements. Moreover, a Floor Area Ratio (FAR) bonus can be given on the condition of planting trees in the plot's surrounding land.

The policy document also describes a Green Network and outlines provisions to have the network attached to any development plan. A Green Network is a system of interconnected green spaces, such as parks, gardens, green roofs, tree-lined streets, and continuous green pathways within an urban area. Lastly, to manage the high population density of Dhaka city, the policy outlines recommended area-wise density planning where the population per acre is fixed by the local authority. These policies mentioned above are all beneficial to reduce the city's air and surface temperature, thereby important measures to curb the UHI impacts.

4.2.1.5 Policies Indirectly Addressing UHI

There are additional policy recommendations regarding proposed land use, environmental protection, and preservation of open spaces and water bodies included in the DSP and DDAP. The policies described below also assist in mitigating UHI, even though the report did not specifically mention them as curbing UHI in Dhaka city.

The policy describes the dependency of human settlements on their surrounding natural environment and explicitly emphasizes the priority of preserving existing vegetation and water bodies by properly documenting these areas in order to maintain a sustainable environment through the evaporative cooling these areas provide. This policy includes the preservation of Bhawal National Park, Bangabandhu Safari Park, Ramna Park and Lake, Dhanmondi Lake, Crescent Lake, Gulshan-Badda

Lake, Gulshan-Banani Lake, Hatirjheel Lake, as well as the Turag, Buriganga, Bangshi, Balu, and Shitalakhya Rivers (see Figure 4.2 for their locations), along with preserving agricultural lands within and around the urban areas.

The policy also advocates for adequate urban open spaces by preserving existing open spaces, and securing future open spaces to promote and enhance livability and quality of life. The policy emphasizes the necessity of parks and playgrounds as integral components of every neighborhood. The report specifically indicates the construction of a large regional park (RP) in each of MPRs no. 2 to 6 (5 regional parks in total) like Ramna Park found in MPR no. 1, 55 water-based parks (WP), 14 large ecological parks (EP) (including Bhawal Forest) and 14 other parks (P) and playgrounds (PG) (2 to 1206 acres of land) to increase the vegetated areas and thereby help in decreasing the urban temperature. Their locations are shown in Figure 4.3.

In addition to green space, the policy addresses the conservation of water bodies to enhance local aesthetics and make them sources of community recreation. Waterbody-centric amusement parks, proposed in the development plans, serve as potential strategies for mitigating the UHI effect through evaporative cooling. However, their implementation requires careful monitoring, as increased humidity combined with high temperatures can significantly impact human health.

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However, their implementation requires careful monitoring, as increased humidity combined with high temperatures can significantly impact human health.

The DDAP policy promotes the development of landscaped green belts along water bodies and the establishment of urban and suburban forestry and greenery by planting trees along the streets, in the road islands, along the right-of-way, and inside paved areas in commercial and residential areas, and car parks to enhance vegetation and reduce the adverse effect of UHI by improving permeable surfaces. The plan proposes the development of an interconnected network of green spaces as linear corridors linking existing major parks, nodes, and open areas. The network would integrate various reserves (designated areas of land set aside for specific purposes) including those for roads, utilities, canals, drainage, railways, streams, rivers, and scenic routes. The policy proposes establishing a green network anchored at the Old Airport site, transforming it into Dhaka's central green park. This network is envisioned to connect key urban green spaces, including Hatirjheel area, linking Ramna Park, Sohrawardy Uddayan towards the south, Sher-E-Bangla Nagar area, National Zoo and Botanical Garden towards the northwest, and Dhanmondi Lake and Pilkhana towards the southwest (see Figure 4.2 for their locations).

Finally, the policy advocates for increasing environmental awareness among citizens through community outreach initiatives such as seminars, workshops, television and newspaper campaigns, public service announcements, and programs focused on reducing resource consumption, minimizing waste production, and improving urban cleanliness. These efforts aim to foster community engagement and motivate collective action to address the UHI issue effectively.

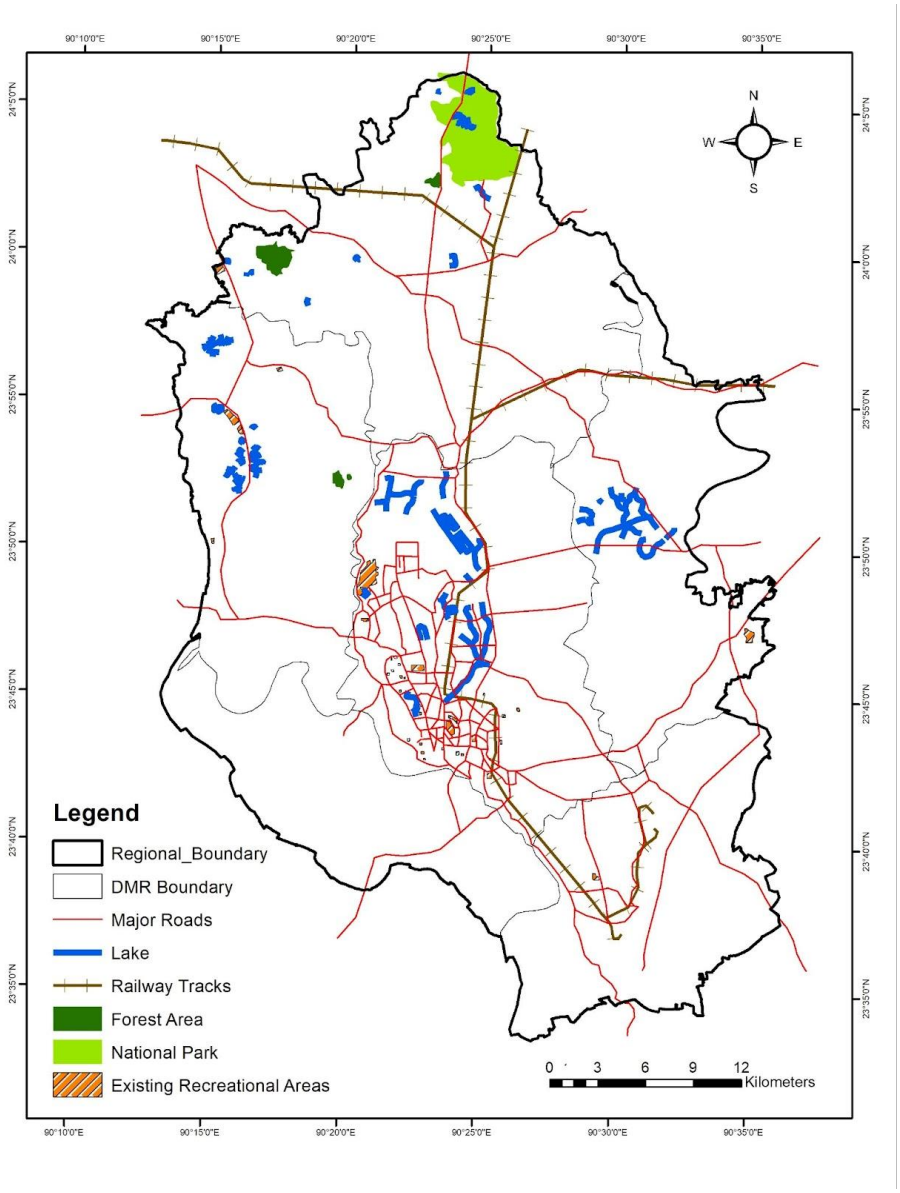

Figure 4.2: Major areas/features targeted for implementation of UHI mitigation within Dhaka Metropolitan Region as presented in RAJUK (2016).

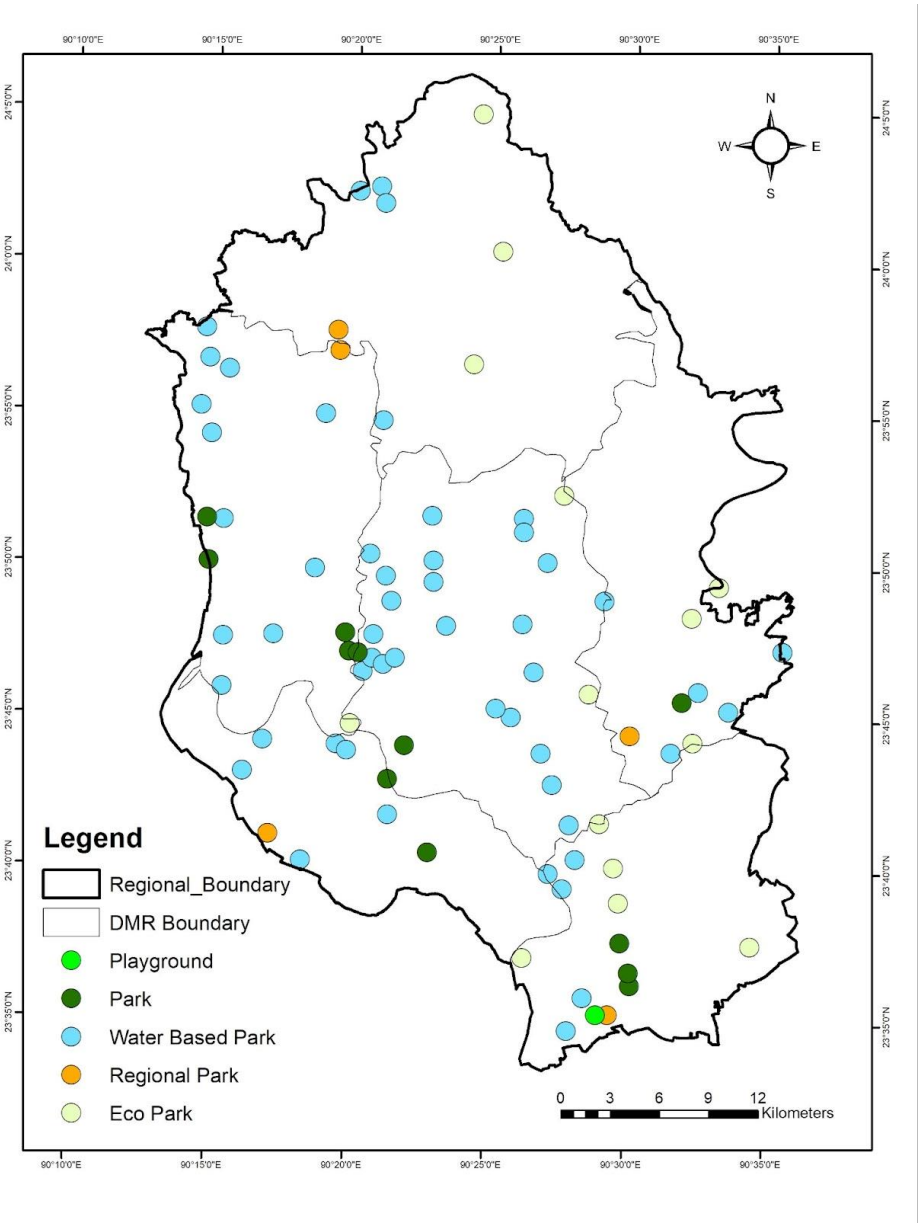

Figure 4.3: Proposed Parks and Playground in DMR Area as presented in RAJUK (2022a).

4.2.2 Chattogram

4.2.2.1 Overview of Plans

Chattogram city has developed several development plans, of which the most recent plans are described in the following paragraphs. These plans were prepared in 1995 to provide guidelines for future city development. The authority is still following those plans, although the authority is now preparing and updating the detailed area plan.

Structure Plan (published in 1995 for the time period of 1995-2015), referred to as the Chattogram Structure Plan (CSP) in this chapter, sets out long-term policies and seven broad objectives for urban development and the use of land in the metropolitan area of Chattogram.

Urban Development Plan (published in 1995 for the time period of 1995-2005), referred to as the Chattogram Urban Development Plan (CUDP) in this chapter, elaborates on the policies of the CSP. This plan is concerned only with the area where the greatest change is expected in the medium term (10 years), and gives greater precision to the CSP policies.

Detailed Area Plan (published in 1995), referred to as the Chattogram Detailed Area Plan (CDAP) in this chapter, provides guidance for areas where major change or action is expected in the short term. For the individual geographic areas of the metropolitan area covered, this plan furthers the policies and proposals of both the CSP and the CUDP and provides more detailed guidance for the control, promotion, and coordination of development.

4.2.2.2 Planning Regions

The CDAP divided the Chattogram development planning area into 12 Detailed Planning Zones (DPZs), as shown in Figure 4.4. A summary of the land area of the 12 DPZs is presented in Table 4.2.

Table 4.2: Summary of 12 Detailed Planning Zones in Chattogram Metropolitan Area.

DPZ	Area Coverage	Total Area (Acres)
DPZ 01	Patenga – Halishahar	12,704
DPZ 02	Agrabad - Kattali	10,085
DPZ 03	Sadarghat - Chawk Bazaar	3,326
DPZ 04	Bakalia - Chandgaon	8,195
DPZ 05	Lalkhan Bazaar - Pahartali	5,914
DPZ 06	Panchlaish - Baizid	9,601
DPZ 07	Silimpur - Kumira	25,546
DPZ 08	Hathazari - Raozan	26,585
DPZ 09	Kulgaon - Halda	7,078
DPZ 10	Madunaghat - CUET	10,985
DPZ 11	Boalkhali - Patiya	15,485
DPZ 12	Anwara - Karnaphuli	35,198

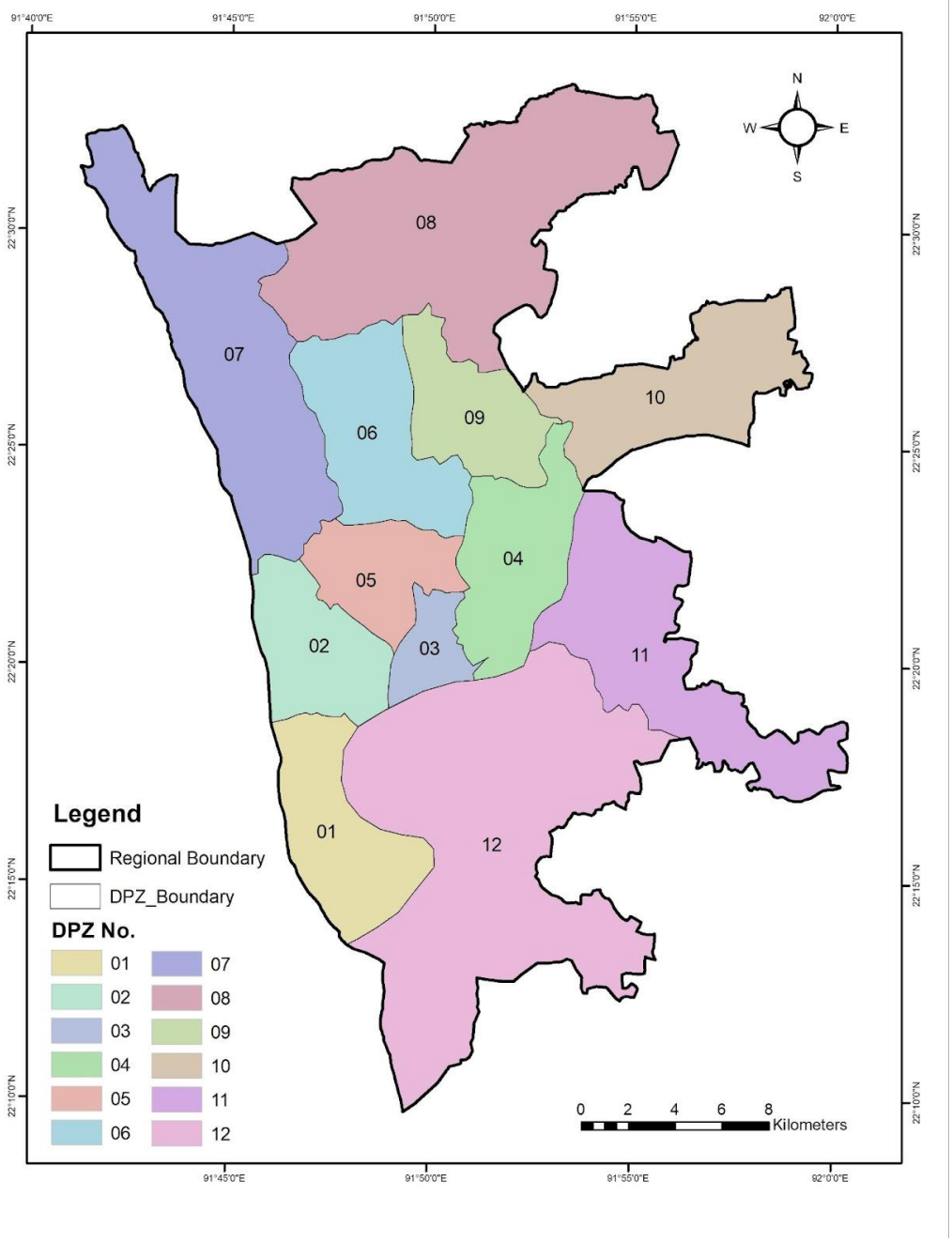

Figure 4.4: Detailed Planning Zones (DPZs) of Chattogram Metropolitan Area (CMA) as presented in CDA (2011).

4.2.2.3 Policies Addressing UHI

There are various policy recommendations regarding urban and rural land development, environmental quality, and flood control and drainage included in the CSP, CUDP and CDAP. While the policies listed below were not specifically described in the policy document to tackle the Urban Heat Island (UHI) issue, they nonetheless contribute to mitigating its effects in Chattogram city.

Relevant policies in the CSP, CUDP, and CDAP include identifying and protecting areas of ecological significance, such as forests and unspoiled coastlines before they are destroyed. The policies suggest that once the initial priority of protection is successfully achieved, measures can be taken to enhance the quality of these areas. The policy also encourages the development of non-urban uses such as agriculture and forestry land on the periphery of the urban areas, which are unsuitable for urban development. The plan identified key areas for policy implementation, including land adjacent to the new coastal embankment on the western side of the city along the Bay of Bengal, and land on the southern bank of the Karnaphuli River (refer to Figure 4.5 for locations). The coastal embankment (an artificially raised earthen ridge used in the fluvial, tidal, and coastal environments) was established to protect the west side of the city from storm surges and coastal erosion.

Another policy recommendation involves the establishment of green corridors to create a network of linear open spaces connecting river valleys and natural drainage canals, enhancing their utility. Additionally, the policy emphasizes repurposing abandoned railway tracks for greening initiatives.

A further applicable policy included the implementation of several “Prestige Projects,” defined as projects that will help residents gain an increased sense of civic pride in their city. These projects included a continuation of the tree planting program

along major road corridors, plus its extension to parks and other open spaces, the creation of a landscaped park on the open space immediately adjacent to Jamiatul Falah Mosque, and further development of the zoological and botanical gardens at Foy's Lake (refer to Figure 4.5 for location) with the long-term objective of transforming it into a regional park.

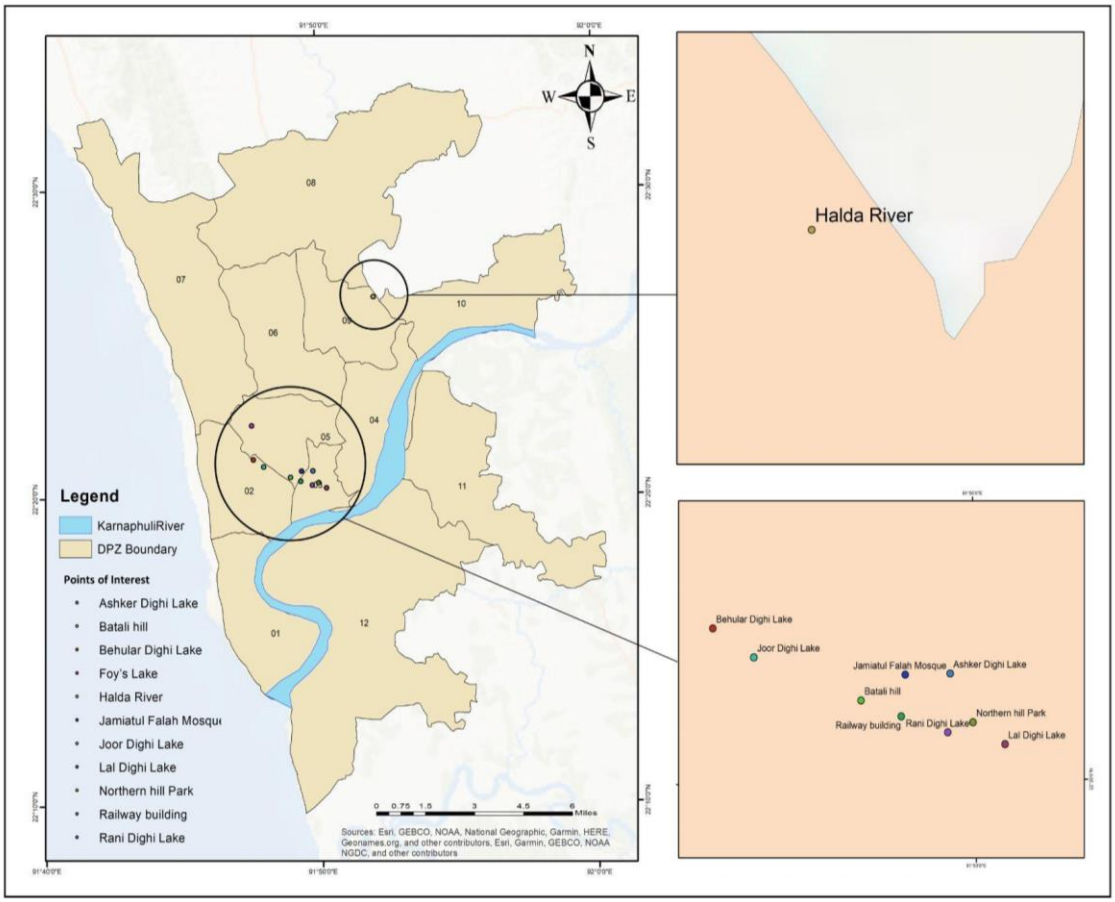

Figure 4.5: Location of areas mentioned in the Chattogram development plans.

The policy recommends protecting, enhancing, and adding more parks, playgrounds, and other significant areas of open space within the city to improve the quality of life. Some major examples include the development of the Karnaphuli and Halda River shorelines, Foy's Lake and the proposed regional park, the area around the railway buildings, and the northern hills, Batali Hill, and the adjacent hills (see Figure 5 for their locations).

The policy also includes implementing no-development zones in areas vulnerable to tropical cyclone surges, areas surrounding the airport, areas aimed at afforestation projects, and undeveloped coasts and estuaries.

This policy includes restoring and preserving canals and lakes in the existing city. Some major existing canals are the Tulatuli, Mirza, Uttara, Shital Jharna, Khandakia, and Shikalbaha canals. Some existing lakes include Lal Dighi, Deba Dighi, Ashker Dighi, Rani Dighi, Behular Dighi, and Joor Dighi Lakes.

The policies mentioned above include increasing vegetation and waterbodies. Vegetation, including tree coverage, parks, playgrounds, agricultural lands, and forested areas, along with water bodies, helps reduce an area's temperature through evapotranspiration that cools the urban environment.

4.2.3 Sylhet

4.2.3.1 Overview of Plans

The city of Sylhet has developed three plans, which were reviewed in this study:

Structure Plan (published in 2011 for the time period of 2010-2030), referred to as the Sylhet Structure Plan (SSP) in this chapter, is aimed to provide a long-term strategy for the development of Sylhet city and its surroundings. The plan indicates the magnitude and direction of future growth of the city and sets forth policy recommendations.

Urban Area Plan (published in 2011 for the time period of 2010-2020), referred to as the Sylhet Urban Area Plan (SUAP) in this chapter, is more elaborate than the SSP and is formulated to guide the future infrastructure development and land use control of Sylhet city.

Detailed Area Plan (published in 2011 for the time period of 3-5 years), referred to as the Sylhet Detailed Area Plan (SDAP) in this chapter, is a series of detailed spatial development plans, including site and services development plans (such as a housing strategy to provide affordable shelter to low-income populations) initiated by the public sector, special development plans, participatory land readjustment plans, guided land development plans, and infrastructure led development plans and area improvement proposals. The aim of SDAP is to prevent haphazard urban development and ensure a livable environment in areas that are likely to be urbanized in the near future.

4.2.3.2 Planning Regions

The entire SSP area is subdivided into 12 Strategic Planning Zones (SPZs) for the purpose of detailed area planning, as shown in Figure 4.6. A summary of the land area of the 12 SPZs is presented in Table 4.3.

Table 4.3: Summary of 12 Strategic Planning Zones (SPZs) in Sylhet Metropolitan Area.

SPZ	Area Coverage	Total Area (Acres)
SPZ 01	Kumargaon Part and Kasba Akhalia	1,693
SPZ 02	Monglichhora, Malnichhora, Hamidpur, Brahmanchhora, Tarapur and Lakkatura TGs	3,976
SPZ 03	Barsala	1,322
SPZ 04	Sadipur 1st Part and Debpur Part	2,304
SPZ 05	Khidirpur, Bahar, Pesh Nowaz, Hajirai, and Sultanpur Chak	4,165
SPZ 06	Kuchai, Palpur Purba, Paschimbag	828
SPZ 07	Ward 25, Ward 26, and Ward 27	1,685
SPZ 08	Ward 08 Ward 09, and Ward 10	1,145
SPZ 09	Ward 02, Ward 11, Ward 12, Ward 13, Ward 14, Ward 15 and Ward 16	942
SPZ 10	Ward 05, Ward 17, Ward 18, Ward 19 and Ward 20	977
SPZ 11	Ward 21 Ward 22, and Ward 23, and Ward 24	1,098
SPZ 12	Ward 01, Ward 03, Ward 04, Ward 06 and Ward 07	903

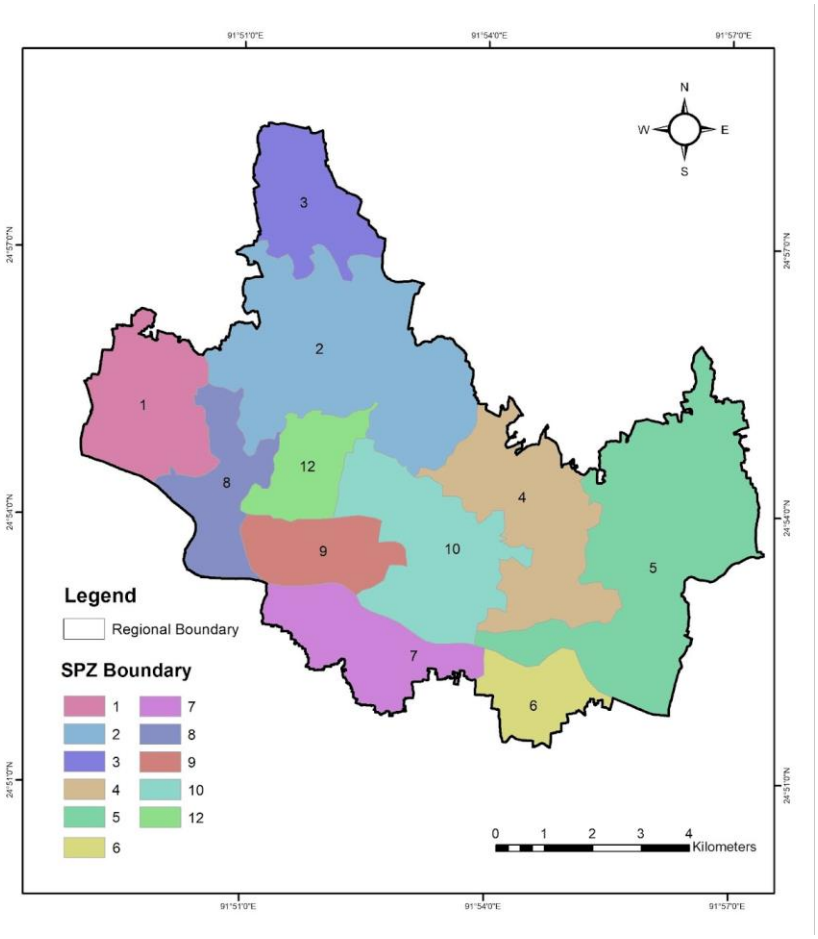

Figure 4.6: Strategic Planning Zones (SPZs) in Sylhet Metropolitan Area as presented in UDD (2011a).

4.2.3.3 Policies Addressing UHI

There are various policy recommendations in the SSP, SUAP, and SDAP regarding conservation and protection of environmentally critical areas, environmental improvement, and recreational park development. While the policies listed below were not specifically mentioned to tackle the UHI issue, they do help to alleviate its effects in Sylhet city.

Sylhet development plan policies include conserving and protecting the following areas: the northern hills, major ponds and lakes, forests, heritage sites, and the Surma River (see Figure 6.7). The preservation and development of open spaces in the form of community-level parks is emphasized with the Surma riverbanks targeted for preservation. The present location of the Central Jail (Sylhet central prison) area has been recommended for relocation and proposed for open space, which will increase the urban open space in the planning area. The policies also note the need to protect the natural drainage system of the city, with Malni and Goali creeks listed as priorities.

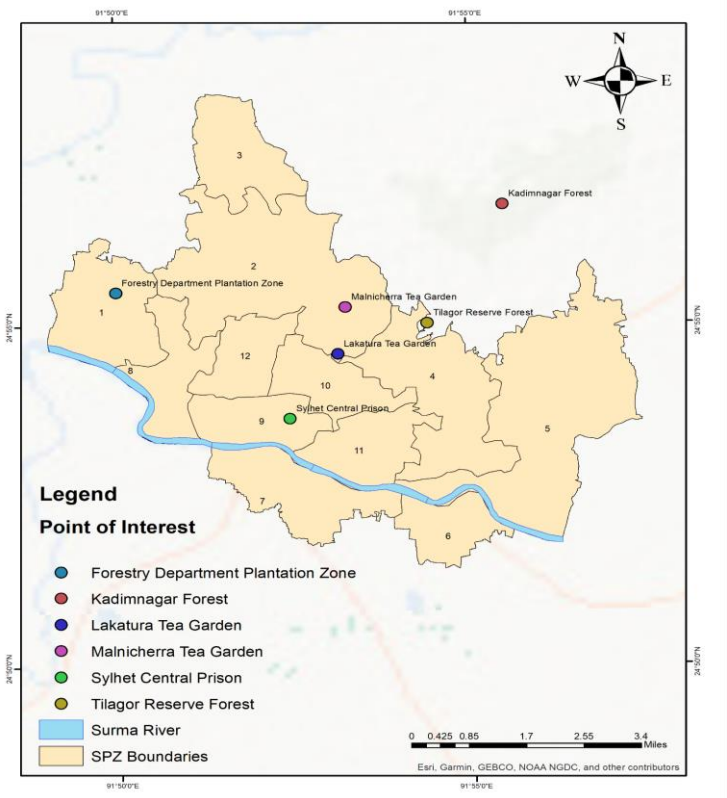

Figure 4.7: Location of areas mentioned in the Sylhet development plans.

Sylhet's existing hilly areas and tea gardens are considered ecological and natural resources of the city, and the policy document explicitly emphasizes their protection under the strategic guideline for open space conservation. The policy document specifically states that disturbing the land surface for urban use or agriculture in the city's northern hills must be stopped to maintain ecological balance and biodiversity. Other policies include developing green belts along the Surma River and other major creeks and canals along with enhancing afforestation. Preservation and restoration of hilly areas and water bodies will help reduce the temperature of Sylhet city, as well as the specific policy recommendation of increased vegetation through an afforestation program will further enhance the mitigation of UHI.

4.3 UHI Mitigation Recommendations

Previous studies outline numerous ways to mitigate the effects of UHI. This section examines these methods and relates their appropriateness and effectiveness in Bangladesh.

Greenery and tree plantation are considered the primary methods to reduce the effect of UHI impact (Santamouris et al., 2019; Akbari et al., 2015; Corburn, 2009; Wang & Akbari, 2016; Yamamoto, 2006; Elsayed, 2012; Nuruzzaman, 2015; Sodoudi et al., 2014). Urban greenery contributes significantly to reduce the harmful impacts of UHI, both directly and indirectly (Aflaki et al., 2017). In fact, greeneries in urban areas reduce the temperature in summer (Chun & Guldmann, 2018), thereby decreasing the energy demand. Urban forestry in the form of increasing urban parks and residential yards can reduce the effects of UHI (Chow & Brazel, 2012). Susca et al. (2011) found a 2°C temperature difference in the most and least vegetated areas of New York City. To increase the greenery and reduce the UHI effect, Singapore's

Urban Redevelopment Authority (URA) has implemented a green plot ratio as part of its efforts to transform the city into a "City in a Garden," where developments are encouraged to achieve a certain GnPR based on the zoning and use of the site. Similar to Singapore, Malaysia has also adopted GnPR in some of its urban planning guidelines to ensure sustainable urban growth and enhance green coverage in its cities.

Green roofs are also considered as an effective mitigation technique for UHI (Akbari et al., 2015; Baniya et al., 2018; Fahed et al., 2020; Lee et al., 2014; Sodoudi et al., 2014) where green roof vegetation's lower temperatures through evapotranspiration (Getter & Rowe, 2006). Simulation models projected a temperature reduction of 2 to 3°C in Toronto City with 50% green roof coverage (Bass et al., 2003); a temperature difference of 2°C in Pennsylvanian cities (Pompeii, 2010); and 3°C temperature drop in Chicago, Illinois (Smith & Roebber, 2011). Shading the outdoor and public spaces in urban areas with trees and green roofs is also considered an important technique in UHI mitigation (Akbari et al., 2015).

Reflective materials used in urban structures are another important factor in reducing the effect of UHI (Akbari et al., 2015; Yuan et al., 2016). Various techniques, such as bright-colored materials, reflective white paints for pavements and surfaces, and white clay tiles, are used on roofs, pavements, and other urban structures to reflect sunlight, reduce the surface temperature, and lessen the impact of UHI. Cool roofs are considered as an effective solution to reduce the UHI intensity with their high albedo (Akbari et al., 2015; Yuan et al., 2016; Wang et al., 2016; Pisello et al., 2016; Takebayashi & Moriyama, 2007).

Cool pavements and road materials that are porous and permeable are another impactful mitigation technique for UHI (Wang et al., 2016; Sen et al., 2019) that

enhance the evaporation cooling process. In addition, vegetation on the sides of the paved sidewalks provide efficient shading (Akbari et al., 2015).

Water bodies have unique thermal properties compared to other natural and man-made features. Due to water's high heat capacity, it warms up and cools down more slowly than other surfaces, helping to mitigate UHI impacts by providing a stabilizing effect on surrounding temperatures (Parison et al., 2020). An increase in water bodies may result in a decrease in temperature because of their evaporative cooling (Robitu et al., 2006).

Various mitigation techniques can be combined to enhance UHI reduction. For instance, in Western Sydney, Australia, Santamouris et al. (2019) evaluated the effects of combining water-based cooling technologies, greenery, and high-albedo materials for roofs and pavements, achieving an average temperature reduction of 1.5°C, with localized reductions up to 10°C near water features. Similarly, in Beirut, Lebanon, Fahed et al. (2020) studied a combination of green spaces, water features, and reflective materials, reducing ambient temperatures by up to 5°C and significantly improving pedestrian comfort in dense urban settings. Wang et al. (2016) found that combining cool pavements, cool roofs, and green models significantly reduced outdoor air temperatures by 0.5 to 0.8°C during the day and lowered Physiologically Equivalent Temperature (PET - a thermal comfort index that quantifies the effects of various environmental factors on human thermal comfort) by an average of 1.8°C in Toronto, Canada, through numerical simulations using the ENVI-met software.

Some of these mitigation strategies, such as increasing greenery and tree plantation, green roofing, shading through vegetation coverage, conserving the existing urban forests, and restoring and preserving existing water bodies, were stated

in the development plans of the study areas of Dhaka, Chattogram, and Sylhet. In particular, the restoration and preservation of water bodies can play a crucial role in mitigating urban heat by enhancing evaporative cooling, although it is equally important to monitor local humidity levels to assess how such cooling effects may interact with high humidity and temperatures to impact human health. One notable example of the restoration of water bodies is the Dhaka Hatirjheel and Begunbari Canal restoration project. The Hatirjheel Project, encompassing 311 acres in Dhaka, sought to achieve stormwater retention, environmental rejuvenation of the Hatirjheel area, and traffic decongestion through strategic infrastructure development. Key components included the re-excavation of Hatirjheel and Begunbari Canal to enhance water retention and transform the area into a freshwater lake, supporting approximately 3.06 billion liters of water in the dry season and 4.81 billion liters in the rainy season (Sen et al., 2022). Safety improvements and the addition of an amphitheater further developed Hatirjheel into a multifunctional urban park, serving as a recreational space for the community (Sen et al., 2022).

Another successful implementation is the Karupannya Rangpur Factory, which exemplifies a ‘green’ architectural paradigm within the rug weaving industry of Bangladesh (Sen et al., 2022). The factory’s design integrates natural elements and traditional knowledge to optimize environmental and energy efficiency (Sen et al., 2022). Spanning approximately 27,870 m^2 and employing a workforce predominantly composed of local women, the factory has achieved an 80% reduction in electricity usage (Sen et al., 2022). It incorporates sustainable water management through reservoirs used for dyeing processes and employs a circular economy model by recycling cotton and garment waste into yarn (Sen et al., 2022). The architecture

features green walls, rooftop gardens, and an effluent treatment plant, contributing to biodiversity conservation and providing a pleasant working environment (Sen et al., 2022). The factory's design, which includes Nandini Park and traditional rural setting, merges modernity with cultural heritage, fostering a sustainable and aesthetically enriched workplace (Sen et al., 2022).

The use of reflective materials, cool roofs, and cool pavements as methods to mitigate UHI effects remains uncommon in Bangladesh. Limited awareness and resource constraints have slowed the adoption of these techniques, which have proven effective in reducing urban heat in other contexts. Expanding the use of these materials could significantly contribute to UHI mitigation by lowering surface temperatures and improving overall urban livability.

4.4 Conclusion

The mitigation of UHI is a multifaceted challenge that requires a comprehensive and integrated approach. The evidence gathered from previous studies underscores the importance of implementing a combination of strategies tailored to the specific needs and characteristics of urban areas along with careful consideration of the climate. Key measures such as increasing urban greenery through parks, green roofs, and vertical gardens, enhancing urban albedo with reflective materials, conserving water bodies as blue spaces, and promoting sustainable urban planning and building practices are vital. The urban development plans of the three studied municipalities (Dhaka, Chattogram, and Sylhet) include a few of these mitigation measures, but limited policies to combat the UHI impacts.

Dhaka's detailed area plan specifically targets the UHI problem in the city, whereas the development plans for Chattogram and Sylhet cities lack direct climate

focused policy guidelines to address UHI issues. The absence of direct policy guidelines in the development plans of Chattogram and Sylhet cities indicates a lack of prioritization of this environmental concern. Chattogram and Sylhet, like Dhaka, are also rapidly urbanizing cities facing similar challenges of urban heat stress. Without explicit policies to combat UHI, these cities may face exacerbated heat-related health risks, reduced air quality, increased energy consumption, and environmental degradation.

An important aspect of all three cities' development plans is that they include policies to increase greenery and water bodies that will reduce temperatures. However, specific policies addressing the UHI problem are critical. Moreover, the development policies must include people's participation, as the role of community engagement in policy support cannot be overstated. The success of UHI mitigation efforts hinges on the active participation of all stakeholders, including local governments, businesses, and residents. Another key consideration is ensuring that UHI mitigation strategies are inclusive and equitable, addressing the needs of vulnerable populations who are disproportionately impacted by extreme heat..

A major challenge is the implementation of UHI mitigation measures within the existing built-up urban areas. However, green retrofitting can be applied as a more cost-effective and feasible measure of UHI mitigation that includes green roofing, rooftop gardening, and green hanging walls.

A major concern to effectively tackle the UHI effect is the lack of implementation of the previous development plans. Unfortunately, there exists a pronounced disparity between the articulated policies and their actual execution within Bangladesh (Mohibbullah et al., 2021). Municipal authorities are responsible for

proposing development plans, overseeing their implementation, controlling development, and managing city growth. Their primary goal is to ensure planned, sustainable urban development and promote a healthy environment. However, these municipal authorities lack sufficient power, resources, and institutional capacity to enforce these plans. Consequently, development plans are not being fully implemented to control and manage the development of the city. Inadequate enforcement and monitoring have led to widespread violations, with many landowners constructing buildings without proper approval. Corruption has also resulted in improper land use and building permits (Mahmud, 2007). As a result, cities are developing chaotically, leading to significant problems, including exacerbating the urban heat island effect.

Besides addressing the existing challenges associated with implementing the development plans, future research should focus on long-term monitoring and evaluation of implemented strategies to refine and optimize UHI mitigation practices continuously. By fostering collaborative efforts and leveraging both traditional and modern solutions, cities can not only mitigate the adverse effects of UHI, but also enhance overall urban resilience and livability. The success of the Hatirjheel Project and the Karupannya Rangpur Factory exemplifies this approach, as both projects contribute not only to reducing the UHI effect but also to enhancing social well-being by providing recreational spaces, improving local air quality, and creating economic opportunities for the community. The path forward lies in a balanced approach that harmonizes environmental sustainability with socio-economic development, ensuring a cooler, healthier, and more sustainable urban future for all.

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Chapter 5

CONCLUSION

The Urban Heat Island (UHI) effect and climate change are deeply interconnected, amplifying each other's impacts and posing a severe threat to urban environments. As global temperatures rise due to climate change, the heat retained by cities intensifies, making urban areas even hotter compared to their rural surroundings. This exacerbation of UHI leads to a vicious cycle where increased temperatures boost energy consumption for cooling, which in turn leads to higher greenhouse gas emissions, further fueling climate change. Mahmud et al. (2021) documented an average temperature rise of 0.5°C between 1976 and 2019 in Bangladesh, with variations across the country. For instance, compared to a 0.5°C rise in the central parts of Bangladesh, including Dhaka and neighboring districts, maximum temperatures rose by 0.9°C in the eastern parts encompassing Chattogram and Sylhet divisions. By 2050, Bangladesh is expected to experience an increase in temperature of about 1.5°C (Mahmud et al., 2021).

Moreover, the heightened temperatures in cities can significantly aggravate the frequency and severity of heat waves, putting additional strain on public health systems and disproportionately affecting vulnerable populations. The compounded stress from UHI and climate change not only degrades the quality of life but also poses challenges to the resilience and sustainability of urban infrastructures. Addressing the UHI effect is thus a critical component of the broader fight against climate change. Implementing green roofs, enhancing urban greenery, using reflective building

materials, and improving urban planning to reduce heat absorption can help mitigate UHI. These measures not only cool down cities but also contribute to lowering overall carbon emissions, creating a positive feedback loop in combating climate change.

The dissertation investigated the complex phenomenon of UHI development (both AUHI and SUHI) in three large cities of Bangladesh, namely Dhaka, Chattogram (previously known as Chittagong), and Sylhet, by addressing several research objectives stated in the introduction. To address the first objective of documenting the overall land use changes in the study areas over the last two decades and quantifying the rate of urbanization, this study classified for each city and for each representative decade, a three-year time composited (for 4 periods) image stack of Landsat satellite data using a pixel-based Random Forest (RF) supervised classification method in the Google Earth Engine (GEE). All three cities showed an increasing trend in the built-up areas replacing agricultural land, forests, and water bodies, indicating a higher level of urbanization. In 2021, the built-up areas constituted 47% of Dhaka's core city area, 37% of Chattogram, and 49% of Sylhet. In contrast, the proposed future expansion areas of these cities are less developed, with impervious surfaces covering only 18% in Dhaka, 13% in Chattogram, and 19% in Sylhet. Over the past two decades, Dhaka has undergone the most significant land use changes, with a 65% change across all land use types, followed by Sylhet with 52% and Chattogram with 48%. The results can guide the development of planning strategies and restoration programs aimed at mitigating the adverse impacts of unplanned urban growth (i.e. UHI) both in the current metropolitan areas and the proposed urban expansion boundaries. Furthermore, uncertainty maps were developed to identify the spatial reliability of the classification, highlighting areas with higher uncertainty that

require more detailed investigation using high spatial resolution imagery or field survey, along with ensuring the land use classification maps are used effectively by urban planners and stakeholders. The second objective of this study was to identify the AUHI (over 35 years) and SUHI (20 years) intensity in the three cities of Bangladesh and document the significant differences between the cities. Previous studies have examined the SUHI situation in major cities of Bangladesh, but studying AUHI and SUHI simultaneously has not been accomplished. Moreover, this study defined the SUHI by comparing the LST differences for the impervious built-up and permeable non-built-up areas, as there is no distinguishable boundary between urban and rural areas in developing countries. To define the AUHI, daytime and nighttime observed air temperature data were used based on available weather stations. Both AUHI and SUHI studies indicate that urban temperatures are rising over time, with a decreasing day-night temperature difference and a more pronounced nighttime AUHI. Across all study areas, the trendline shows a statistically significant increase in nighttime air temperatures. With regards to the SUHI analysis, Dhaka exhibits the highest daytime SUHI intensity, while Chattogram has the highest nighttime SUHI intensity. The spatial distribution of LST shows that the urban core experiences the highest temperatures in all three cities influenced by impervious surfaces and sparse vegetation cover. However, notable areas in the city of Dhaka have much lower temperatures associated with the abundance of trees, parks, and open spaces in Ramna, Dhaka University and BUET areas, in comparison to other areas such as Motijheel (Commercial Business District), Karwan Bazar (institutional and shopping centers), and Moghbazar (mixed residential and commercial land use) that underscores the importance of greenery in urban settings (RAJUK 2022a). Statistical analysis such as

Mann-Kendall test and *t*-test further revealed significant increases in daytime and nighttime temperatures in urban areas compared to rural areas, with urban centers exhibiting a stronger warming trend. This confirms the intensifying UHI effect, particularly in the nighttime, with urban areas showing more pronounced temperature increases.

To reduce the adverse impact of UHI, the third and final objective of this dissertation evaluates the UHI mitigation measures addressed in the existing municipal development plans and previous studies mitigation measures. The existing development plans have incorporated several policies to improve the city's environmental condition and reduce the temperature by suggesting the increase in vegetation (parks, playgrounds, open spaces), restoration of waterbodies, and promoting green infrastructures (green roofing, rooftop gardens, and vertical green walls). One major problem faced by the municipal authority is the lack of implementation of these plans. Municipal authorities must take appropriate measures to ensure proper implementation of the proposed policies, that will result in sustainable city development combating the adverse effects of the UHI. Moreover, the success of UHI mitigation efforts hinges on the active participation of all stakeholders, including local governments, businesses, and residents.

An advantage of this study is its use of freely available medium- and coarse-resolution satellite data. However, the use of higher-resolution data would enhance the land use classification accuracy given Bangladesh's heterogeneous land surfaces of small plots of different land use types. Additional weather station data may also provide more subtle variations of the UHI results. Only one weather station in each city and one in the nearby rural setting were available with a long-term record of more

than 30 years. Future studies, supported by adequate funding, could benefit from the installation of weather instruments at multiple locations across the city and its suburban periphery. Combined with higher-resolution imagery, this approach would enable more detailed and spatially varied analyses of urban and suburban UHI dynamics. However, even with these limitations, the research shows significant results that can be considered in the future planning and green retrofitting of the cities to confront the adverse effects of UHI.

Overall, tackling UHI is not merely about improving urban comfort - it's an urgent imperative for climate action, demanding immediate and sustained efforts to create cooler, more sustainable, and livable cities in the face of a warming world. As highlighted by the Intergovernmental Panel on Climate Change (IPCC), the urban poor in Asia will suffer the most from extreme heat, with temperatures pushing the boundaries of survivability across South Asia. In fact, by 2080, up to 1.1 billion urban dwellers could experience extreme heat lasting over 30 days a year (SEforALL, 2022). It is crucial to integrate urban greening not only as a strategy for mitigating UHI but also as a way to reduce emissions, enhance health outcomes, and improve water management. Moreover, governance, policy planning, and investments in health and food systems are essential for closing adaptation gaps. The IPCC emphasizes the importance of targeted investments and effective heat action plans, as well as the need for improved data and capacity building to address heat vulnerability hotspots. We must act now to cool our cities and protect our communities.

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Appendix A

GOOGLE EARTH ENGINE (GEE) CODES

```
//Cloud masking
var maskL8 = function(image) {
  var qa = image.select('QA_PIXEL');
  var mask = qa.bitwiseAnd(1 << 4).eq(0);
  return image.updateMask(mask);
};

var imageB = ee.Geometry.Rectangle(90.33, 23.67, 90.5, 23.9);
////////////////////// PERIOD 01 ////////////////////////////////
var y1coll = ee.ImageCollection('LANDSAT/LT05/C02/T1_TOA')
.filterDate('2001-01-01','2001-04-30')
.filterBounds(imageB)
.map(maskL8)
.select('B1', 'B2', 'B3', 'B4', 'B5', 'B6', 'B7');

var y2coll = ee.ImageCollection('LANDSAT/LT05/C02/T1_TOA')
.filterDate('2000-01-01','2000-04-30')
.filterBounds(imageB)
.map(maskL8)
.select('B1','B2', 'B3', 'B4', 'B5', 'B6', 'B7');
```

```
        var y3coll = ee.ImageCollection('LANDSAT/LT05/C02/T1_TOA')
        .filterDate('1999-01-01','1999-04-30')
        .filterBounds(imageB)
        .map(maskL8)
        .select('B1','B2', 'B3', 'B4', 'B5', 'B6', 'B7');

        var collection_merge1 =
ee.ImageCollection(y1coll.merge(y2coll.merge(y3coll)));
        var image1 = collection_merge1.reduce(ee.Reducer.median());
        var NDVI = image1.normalizedDifference(['B4_median',
'B3_median']).rename('NDVI');
        var NDBI = image1.normalizedDifference(['B5_median',
'B4_median']).rename('NDBI');
        var bu = NDBI.subtract(NDVI);
        var mndwi = image1.normalizedDifference(['B2_median',
'B5_median']).rename('MNDWI');
        var NDBal = image1.normalizedDifference(['B5_median',
'B7_median']).rename('NDBAL');

        var combine =
image1.addBands(NDVI).addBands(bu).addBands(mndwi).addBands(NDBal);
        //print (combine);
```

```
//////////////////// PERIOD 02 ////////////////////////////////

var y1coll2 = ee.ImageCollection('LANDSAT/LT05/C02/T1_TOA')
.filterDate('2001-05-01','2001-08-31')
.filterBounds(imageB)
.map(maskL8)
.select('B1','B2', 'B3', 'B4', 'B5', 'B6', 'B7');

var y2coll2 = ee.ImageCollection('LANDSAT/LT05/C02/T1_TOA')
.filterDate('2000-05-01','2000-08-31')
.filterBounds(imageB)
.map(maskL8)
.select('B1','B2', 'B3', 'B4', 'B5', 'B6', 'B7');

var y3coll2 = ee.ImageCollection('LANDSAT/LT05/C02/T1_TOA')
.filterDate('1999-05-01','1999-08-31')
.filterBounds(imageB)
.map(maskL8)
.select('B1','B2', 'B3', 'B4', 'B5', 'B6', 'B7');

var collection_merge2 =
ee.ImageCollection(y1coll2.merge(y2coll2.merge(y3coll2)));
var image2 = collection_merge2.reduce(ee.Reducer.median());
```

```
        var NDVI2 = image2.normalizedDifference(['B4_median',
'B3_median']).rename('NDVI2');
        var NDBI2 = image2.normalizedDifference(['B5_median',
'B4_median']).rename('NDBI2');
        var bu2 = NDBI2.subtract(NDVI2);
        var mndwi2 = image2.normalizedDifference(['B2_median',
'B5_median']).rename('MNDWI2');
        var NDBal2 = image2.normalizedDifference(['B5_median',
'B7_median']).rename('NDBAL2');

        var combine2 =
image2.addBands(NDVI2).addBands(bu2).addBands(mndwi2).addBands(NDBal2);
        //print (combine2);

        ////////////////////// PERIOD 03 ////////////////////////////////

        var y1coll3 = ee.ImageCollection('LANDSAT/LT05/C02/T1_TOA')
        .filterDate('2001-09-01','2001-12-31')
        .filterBounds(imageB)
        .map(maskL8)
        .select('B1','B2', 'B3', 'B4', 'B5', 'B6', 'B7');

        var y2coll3 = ee.ImageCollection('LANDSAT/LT05/C02/T1_TOA')
        .filterDate('2000-09-01','2000-12-31')
```

```
        .filterBounds(imageB)
        .map(maskL8)
        .select('B1','B2', 'B3', 'B4', 'B5', 'B6', 'B7');

        var y3coll3 = ee.ImageCollection('LANDSAT/LT05/C02/T1_TOA')
        .filterDate('1999-09-01','1999-12-31')
        .filterBounds(imageB)
        .map(maskL8)
        .select('B1','B2', 'B3', 'B4', 'B5', 'B6', 'B7');

        var collection_merge3 =
ee.ImageCollection(y1coll3.merge(y2coll3.merge(y3coll3)));
        var image3 = collection_merge3.reduce(ee.Reducer.median());

        var NDVI3 = image3.normalizedDifference(['B4_median',
'B3_median']).rename('NDVI3');
        var NDBI3 = image3.normalizedDifference(['B5_median',
'B4_median']).rename('NDBI3');
        var bu3 = NDBI3.subtract(NDVI3);
        var mndwi3 = image3.normalizedDifference(['B2_median',
'B5_median']).rename('MNDWI3');
        var NDBal3 = image3.normalizedDifference(['B5_median',
'B7_median']).rename('NDBAL3');
```

```
var combine3 =
image3.addBands(NDVI3).addBands(bu3).addBands(mndwi3).addBands(NDBal3)//.a
ddBands(combine1);
//print (combine3);

////////////////////// PERIOD 04 ////////////////////////////////

var stdIMAGE = ee.ImageCollection('LANDSAT/LT05/C02/T1_TOA')
.filterDate('2001-01-01','2001-12-31')
.filterBounds(imageB)
.map(maskL8)
.select('B1','B2', 'B3', 'B4', 'B5', 'B6', 'B7')

var imageStdev = stdIMAGE.reduce(ee.Reducer.stdDev());

var NDVI1 = imageStdev.normalizedDifference(['B4_stdDev',
'B3_stdDev']).rename('NDVI_stdDev');
var NDBI1 = imageStdev.normalizedDifference(['B5_stdDev',
'B4_stdDev']).rename('NDBI_stdDev');
var bu1 = NDBI1.subtract(NDVI1);
var mndwi1 = imageStdev.normalizedDifference(['B2_stdDev',
'B5_stdDev']).rename('MNDWI_stdDev');
var NDBal1 = imageStdev.normalizedDifference(['B5_stdDev',
'B7_stdDev']).rename('NDBAL_stdDev');
```

```
var combine1 =
imageStdev.addBands(NDVI1).addBands(bu1).addBands(mndwi1).addBands(NDBal
1);
//print (combine1);

var allcombine =
combine.addBands(combine1).addBands(combine2).addBands(combine3);
//print (allcombine);
var bands = ['B1_median', 'B2_median', 'B3_median', 'B4_median',
'B5_median', 'B6_median', 'B7_median', 'NDVI', 'NDBI', 'MNDWI', 'NDBAL',
 'B1_stdDev', 'B2_stdDev', 'B3_stdDev', 'B4_stdDev', 'B5_stdDev',
'B6_stdDev', 'B7_stdDev', 'NDVI_stdDev', 'NDBI_stdDev', 'MNDWI_stdDev',
'NDBAL_stdDev',
 'B1_median_1', 'B2_median_1', 'B3_median_1', 'B4_median_1',
'B5_median_1', 'B6_median_1', 'B7_median_1', 'NDVI2', 'NDBI2', 'MNDWI2',
'NDBAL2',
 'B1_median_2', 'B2_median_2', 'B3_median_2', 'B4_median_2',
'B5_median_2', 'B6_median_2', 'B7_median_2', 'NDVI3', 'NDBI3', 'MNDWI3',
'NDBAL3'];

 print ('Good job! Alhamdulillah');

//////////////////////////////////////////
```

```
//var classtable =
builtup.merge(agri).merge(forest).merge(water).merge(barren);
var training = allcombine.select(bands).sampleRegions({
  collection: classtable1,
  properties: ['landcover'],
  scale: 30
});

var classifier = ee.Classifier.smileRandomForest({
  numberOfTrees: 100,
  minLeafPopulation: 3,
  bagFraction: 0.5,
  seed: 0,
}).setOutputMode('MULTIPROBABILITY').train({
  features: training,
  classProperty: 'landcover',
  inputProperties: bands
});

// Classify the image
var classified = allcombine.select(bands).classify(classifier);

// Extract the probabilities for each cover type
```

```
var probabilities = classified.arrayFlatten([['builtup', 'agri', 'forest', 'water',
'barren']]);

// Export

Export.image.toDrive({image: probabilities,
  description: 'Uncertainty Map of Dhaka 2001',
  scale: 30,
  region: geometry});
```