Determination and Mitigation of Urban Heat Island (UHI) In Lahore (A comparative Study of Landsat 8&9)

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The term "Urban Heat Island" (UHI) refers to a city or metropolitan area that is significantly warmer than its surroundings. Heatwaves are one of the most visible hazards associated with UHI, that intensified exponentially over the last two decades. The overall approach of the study is initially based on a review of the literature and qualitative studies. The findings were applied to the case study to obtain empirical shreds of evidence. The study investigated the spatiotemporal urbanization trends and their impacts on UHI in Lahore, Pakistan, using multiple datasets. By identifying thermal drivers and simulating the spatial pattern, the direct relationship between development patterns and thermal properties can be visualized. To identify hot spots multi-temporal Landsat TM/OLI satellite images were processed using GIS and remote sensing techniques. It also investigates urban green spaces using spectral indices like the Normalized Difference Vegetation Index (NDVI). The findings indicate that Lahore's urbanization trend is intensifying in both existing and newly proposed zones which increases the pressure on land use planning. The negative correlation between Land Surface Temperature (LST) and NDVI confirms urban sprawl at the expense of green spaces, reshaping and aggregating the UHI profile of Lahore. These methodologies were combined to create UHI mitigation strategies that may aid communication among various stakeholders, including those in academia, development authorities, planners, and practitioners of the built environment. LST calculation by Landsat 9 proved efficient in comparison to Landsat 8 whch may be due to improvement in spatial and spectral domain in architectural design Landsat series.

Keywords: Urban Heat Island (UHI); Land Surface Temperature (LST); Normalized Difference vegetation Index (NDVI; Landsat; Lahore.

Introduction

World is rapidly urbanizing, with cities expected to expand with roughly 68 percent of the population by 2050 [1]. This increase in urban population is exacerbating several human development issues, such as poor infrastructure, economic disparities, unlivable social conditions for residents, and environmental concerns on both natural and built-up environments, where the effects of climate change are adding fuel to furry [2], [6]. The IPCC Sixth Assessment Report (AR6) warns of an exponential increase in temperature in less than a decade. It also highlights human activities that are exacerbating the situation and causing unprecedented and sometimes irreversible changes owing to climate change [7].

Migration trends toward urban areas cast its impact on spatial morphology and leads to the transformation of peri-urban areas into dense urban centers [8]. This reduces green spaces and increases impervious surfaces [9]. This gives rise to UHIs, which have an impact on the warming trend, with the UHI effect accounting for about 3% to 36% of global warming, respectively [10]. If similar practices continue, urban climate risks with the frequent episode of heatwaves will increase manifold [11]. The phenomenon has exacerbated local climatic conditions, with observed warming trends and increases in mean and extreme precipitation over and downwind of cities, particularly in annual mean minimum temperature and increases in mean and extreme precipitation over and downwind of cities [12],[13].

Climate action and sustainable development have been echoed in the United Nations (UN) "Sustainable Development Goals"(SDGs) presented in 2015. Whereas goals 11 and 13 (Sustainable Cities and Communities & Climate Action) focused on city sustainability while mitigating the effects of climate change [14]-[17]. The emission of Greenhouse gases from industries, transportation, and different energy resources, coupled with urban characteristics such as high density and functions amplifies the environmental, social, and health risks, making residents susceptible to extreme weather events and climate change [18]-[21].

The phenomena of climate change and its related impact are intensified and frequent in the last two decades in all corners of the world. Many developing countries in South Asia, including Pakistan, are highly vulnerable to climate change, which causes fluctuations in temperature and rainfall patterns [22], [23]. Pakistan's urban areas are becoming hotspots for frequent extreme climatic events, with rapid urbanization and poor land-use planning adding fuel to the fire [24]-[26]. According to a World Bank Group and Asian Development Bank report on Pakistan's climate risk country profile, an estimated temperature rise of 1.3°C–4.9°C is expected by the 2090s. Heatwaves became more common, affecting approximately 65,000 people who were hospitalized with heatstroke during Pakistan's 2015 heatwave [27],[28].

Pakistan is determined to contribute to the Paris Agreement under the "United Nations Framework Convention on Climate Change," to reduce its greenhouse gas emissions by 20% by 2030. National Climate Change Policy (NCCP 2013) stresses adaptation and mitigation and suggests incorporating them in short – medium- and long-term implementation policies for different sectors. However, its implementation is nonetheless, a significant challenge that has been identified by the ADB in its 2017 report on Pakistan's climate change profile, and pointed out climate change adaptation experience of Pakistan is still at the nascent stage [29]-[31].

As established UHI will have far-reaching consequences for health, society, and the infrastructure that underpins cities. It may have an impact not only on agriculture, and human

health, but also on human settlement patterns, energy use, transportation, industry, environmental quality, and other infrastructure-related aspects that affect the quality of life [32]. According to the aforementioned narrative, it is becoming increasingly important to determine and device effective UHI mitigation strategies that would allow sustainable developments. Hence this paper investigates the factor which causes UHI formation, particularly in Lahore metropolitan areas utilizing GIS and remote sensing techniques. Using those assessments suggests some solutions and policy support mechanisms from an urban design and planning perspective which would mitigate the UHI more effectively.

Material and Methods.

This study is interdisciplinary and is based on deductive reasoning. The goal of the literature review was to establish a theoretical foundation to better understands the causes and treatments for UHI and aid a basic understanding of urban planning and design processes, to address the thermal comfort of cities. This combination of different methodologies was utilized to produce more reliable research results.

Factorization of Urban Heat Island

The higher temperature in central areas of cities as compared to the surrounding or suburban area is referred to as the Urban Heat Island (UHI) [33]-[35]. The risk of the heatwave is linked to the urban heat island. Specific causes give rise to UHI which is formed by differences in the thermal properties, moisture content, and aerodynamic properties of urban and rural geography, such as pollution in the air, anthropogenic heat, and surface 'waterproofing''. Hindrance to the flow of air occurred due to higher rugosity and surface geometry are prime reasons to raise UHI. Each of which represents a change to the pre-urban environment brought about by urbanization [36]-[38]. The microclimate is formed directly as a result of albedo. The albedo of a city depends arises due to factors such as surface orientation, heterogeneity, roof and pavement materials, and so on [39]-[42]. The low albedo of the surface stores more solar energy and gave rise to urban temperature.

Higher human density in city centers results in CO_2 emissions from various sources such as the use of air conditioners, vehicular emissions, and so on. Co_2 is a greenhouse gas that stores heat and raises the temperature of the atmosphere. Hence, Population size must also be considered while calibration UHI [43]. Where changes in LULC to meet the demand for various urban facilities raises the surface temperature [44]. That destruction also reduces the efficiency of the cooling system and thus the process's creation. The multilayer buildings in urban areas are composed of different construction materials and height trapped air which is known as the urban canopy. The formation of an urban canopy exacerbates UHI. Beside Wind Shielding the presence of Pollutants in the Air is prevalent in urban areas, particularly in city centers. The Pollutants from industrial exhaust gases are released in the radiation [45].

As a result, the temperature rises, and the microclimate effect intensifies. The combination of all those causing factors and leading hazards exacerbate UHI and heatwaves.

To better understand the phenomenon, the aforementioned discussion of the relationship among the factors can be placed and visualized in form of the UHI crunch model (Figure 2).
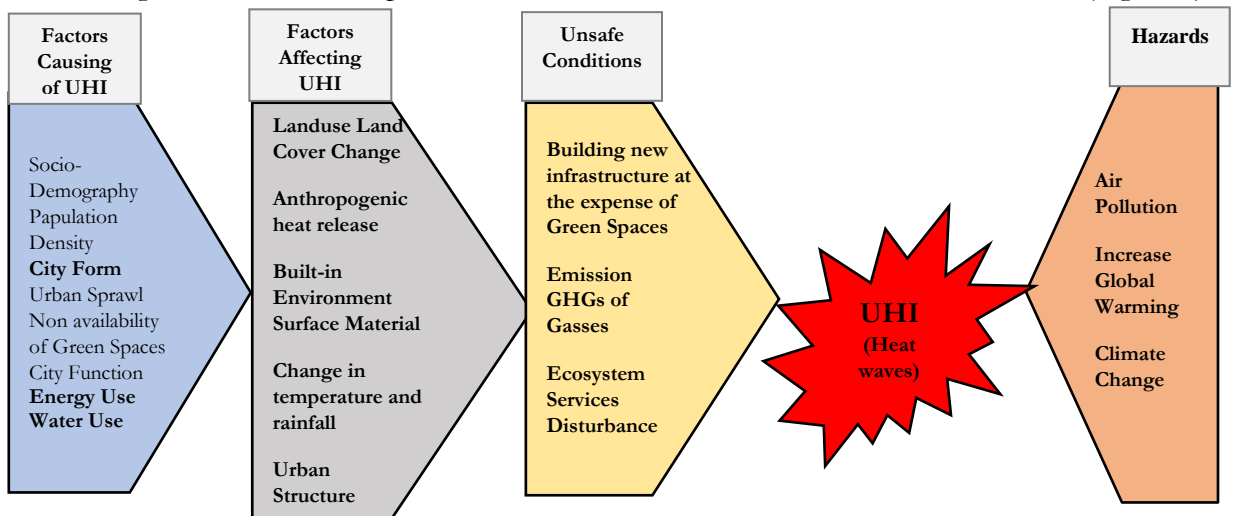

Figure 1: Crunch Model for Heat Waves and Urban Heat Island
Source: Adapted from Blaikie, Wisner, et al (1994) [46].

The case of Lahore.

Lahore is the capital city of Punjab and 2nd most populous city of Pakistan having population of 11.13 million [47]. It is located between 34° 9' - 34° 13' N and 74 Degree 01 Minute – 74-degree 39-minute E (Figure 3). The total land area of Lahore is 1014 km2 at an elevation of 216 m ASL [48]. Lahore is predominantly a monocentric city and administratively, divided into nine zones and one cantonment [49]. The city features a climate (Köppen climate classification *BSh*) with five seasons [50]. Amongst the most recipient districts of Punjab Lahore receives the highest percentage of migrants (23% of total) last decade [51]. The growth is a primary cause of rapid urbanization with haphazard sprawl in the city [52]. Sharp population growth and economic development coupled with increased urbanization and land encroachment caused the reduction of vegetation cover hence deteriorating the urban environment [53]. Matthews et al. ranked Lahore amongst the most vulnerable in wake of extreme heat which increases the high mortality risk due to heat strokes [54].
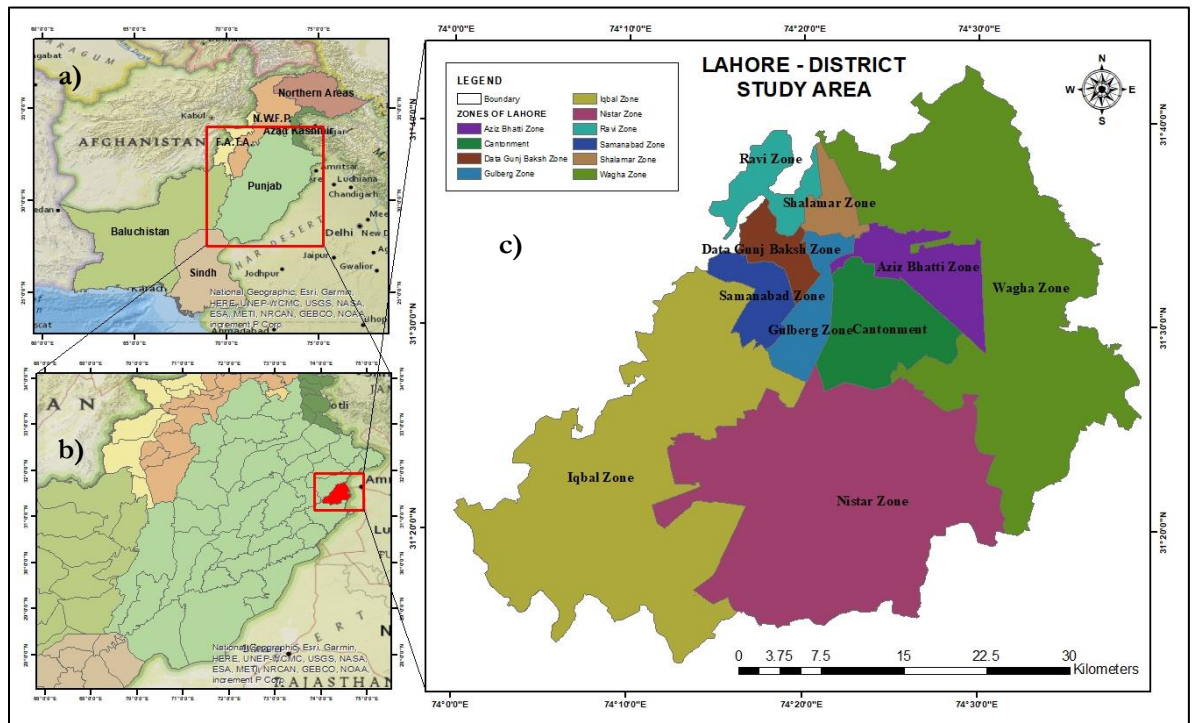
Figure 2. Study area map. a) The administrative boundaries map of Pakistan. b) The administrative boundaries map of Punjab c) The administrative zones of Lahore.
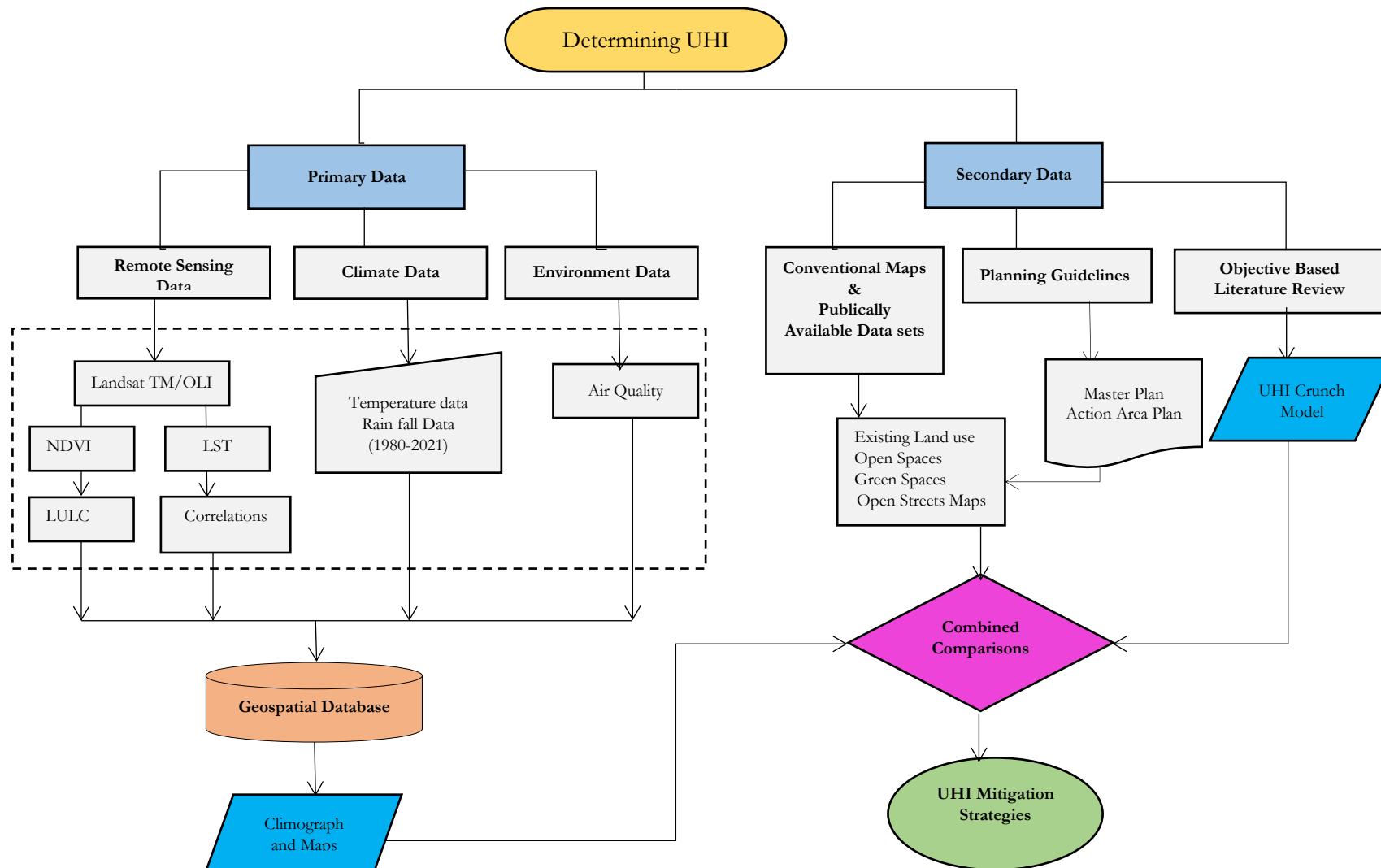
Figure 3: Theoretical Research Methodology
Source: Authors

Data Collection.

To evaluate the calibrated land surface temperature for selected years in Lahore Remote sensing data was collected. Detail is given in Table 1 from the United States Geological Survey (USGS) website using its online interface, Earth Explorer platform [55].

Table 1: Details of Satellite data

Year	Sensor Type	Spatial Resolution (m)	Spectral Resolution	Spatial & Spectral Resolution of bands used	Acquisition Date
1995	Landsat4-5 Thematic Mapper	30*30	7 bands	1-7(30*30)	02-June-1995
2008	Landsat 4-5 Thematic Mapper	30*30	7 bands	1-7(30*30)	05-June-2008
2015	Landsat 8 Operational Land Imager	30*30	11 bands	4,5(30*30) & 10 (100*100)	22-June-2015
2021	Landsat 8 Operational Land Imager	30*30	11 bands	4,5(30*30) & 10 (100*100)	05-June-2021
2022	Landsat 9 Operational Land Imager-2 & Thermal Infrared Sensor 2 (TIRS-2)	30*30	11 Bands	4,5(30*30) & 10 (100*100)	1-May-2022

Data Processing and Analysis

Since the study utilized multiple resources and varied sets of data each data set has been processed accordingly which will be discussed in the following sections.

Metrological Data

$$TOA\ (Top\ of\ Atmospheric)\ =\ AL + ML * Q$$

Where:
ML = Band-specific multiplicative rescaling factor
Qcal = corresponds to band 10,
AL = Band specific additive rescaling factor from the metdata

$$L\lambda = Grescale * QCAL + Brescale$$

Where :
Lλ = Spectral Radiance
QCAL = The quantized calibrated pixel value in DN

$$BT = (K2/ln\ ((K1/L) + 1)) - 273.15$$

Where:
L = TOA
K2=321.0789
K1=1260.56

$$NDVI = (Band\ 5 - Band\ 4) / (Band\ 5 + Band\ 4)$$
$$PV = Square\ ((NDVI + NDVI\ min) / (NDVI\ max - NDVI\ min))$$
$$Emissivity\ (\text{€}) = 0.004 * PV + 0.98$$
$$LST = BT / (1 + (10.8 * BT / 14388) * Ln(\text{€}))$$

A climograph of Metrological data of Lahore from the year 1980-to 2017 was created. The data comprises maximum and minimum average monthly temperatures and precipitations of Lahore. The graphs were plotted against the data, on MS Excel, and linear trend Lines have used with temperature (°C) precipitation (mm) to demonstrate data movement over a selected period in the

city of Lahore.

Remote Sensing Data

a) Estimation of LST & Co-Relation of LST-NDVI

In general, UHI based on Landsat-LST executes hot sunny days along with other selected indicators, such as acquisition time, and the weather conditions [56]. Likewise, for the current study, the Land Surface Temperature (LST) was calculated using successive procedures using set of equation for digital numbers (DN) of the thermal bands 6 and 10 for Landsat 4-5 TM Band Landsat 8respectively. Normalize Difference Vegetation Index (NDVI) for each data set has been processed which provides the sum and quality of vegetation at the earth's surface.
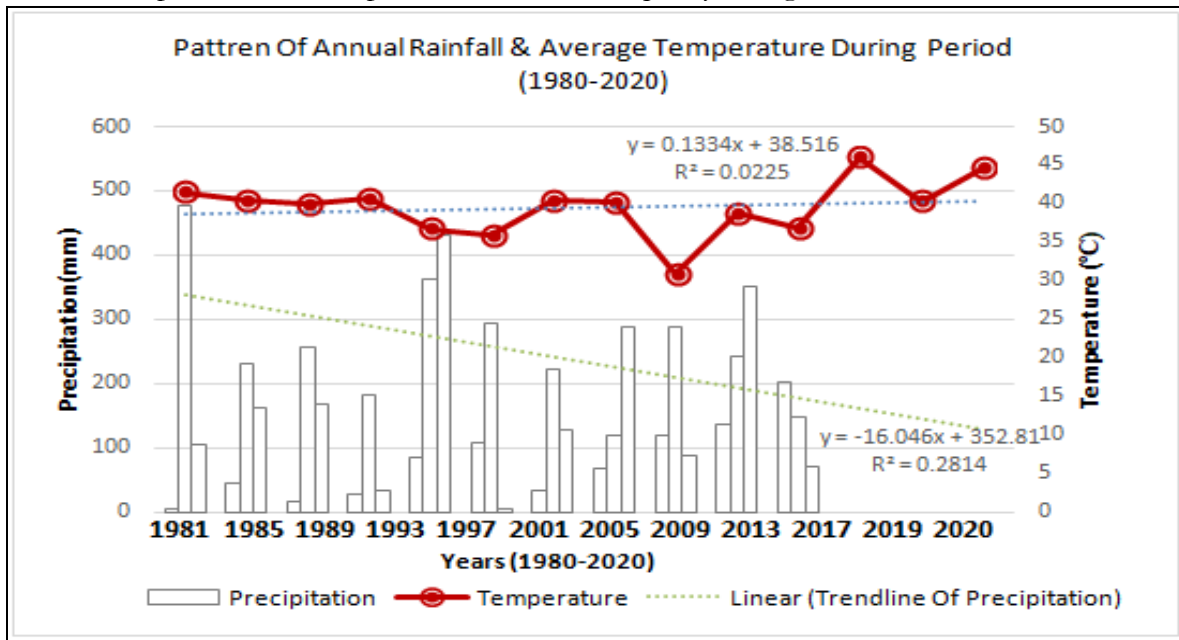

Figure 4: Climograph of Lahore (1980- 2021) Data Source: PMD Lahore

LULC Classification

Amongst the different image classification methods supervised algorithms; offer good results [57]. The LULC change has been calculated using a supervised classification that was performed using the Maximum Likelihood technique. Images were classified into four major LULC groups for 1995, 2008, 2015, and 2021 encompassing built-up, green spaces, water bodies, bare terrain

Results and Discussion

The outcomes of the methods stated in section 3 are described in this section.

Changes in Climate Change Parameters

The analysis of temperatures graphs shows the temperature continues to rise year after year with an increasing trend, particularly after the year 2017 and where the years 2019 and 2021 are the highest so far. The bars demonstrate the precipitation patterns where the month of July is recorded as the wettest month of every year with fluctuating and declining trends in successive years. Thus, the results indicate between 1980 and 2017, there are significant precipitation changes and shifts, with precipitation percentages shifting from approximately 100% in 1980 to 50% in 2021. There is a temperature shift of 4.8°C from 1995

to 2021(Figure 4). This Rising temperature trend and precipitation fluctuations confirmed a significant climatic change in Lahore from 1980-to 1990 as the base year.

Changes in Landuse Land Cover (LULC) Lahore

Noteworthy changing patterns in the classified satellite imagery from 1995-2021 were analyzed. The LULC maps indicated a steady rise in the built-up area (59%) and a decreasing trend in green areas (-58%) (See Figure: 5, Figure: 6, and Table: 2). Over the last two decades, the percentage of built-up bare soil and barren land has also decreased. The trend analysis shows the unremitting change in LULC is taking place where the physical development taking place in northwest, north-east, and north-south directions at expense of vegetation and open areas. Similar results were obtained by another study of Lahore for the years 2000-2020[58].
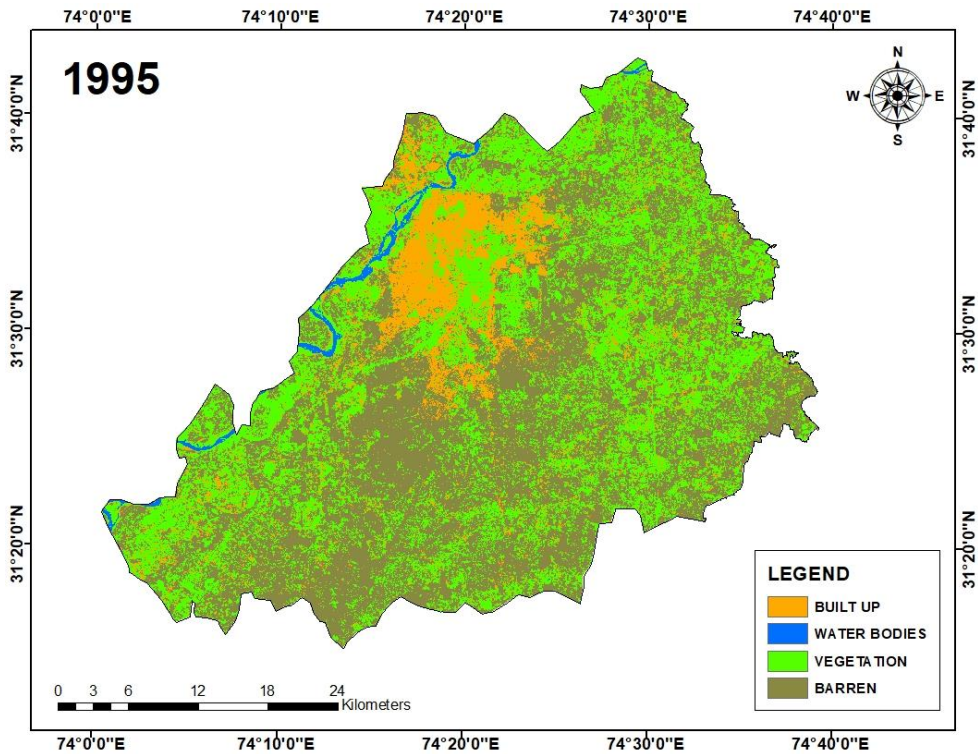

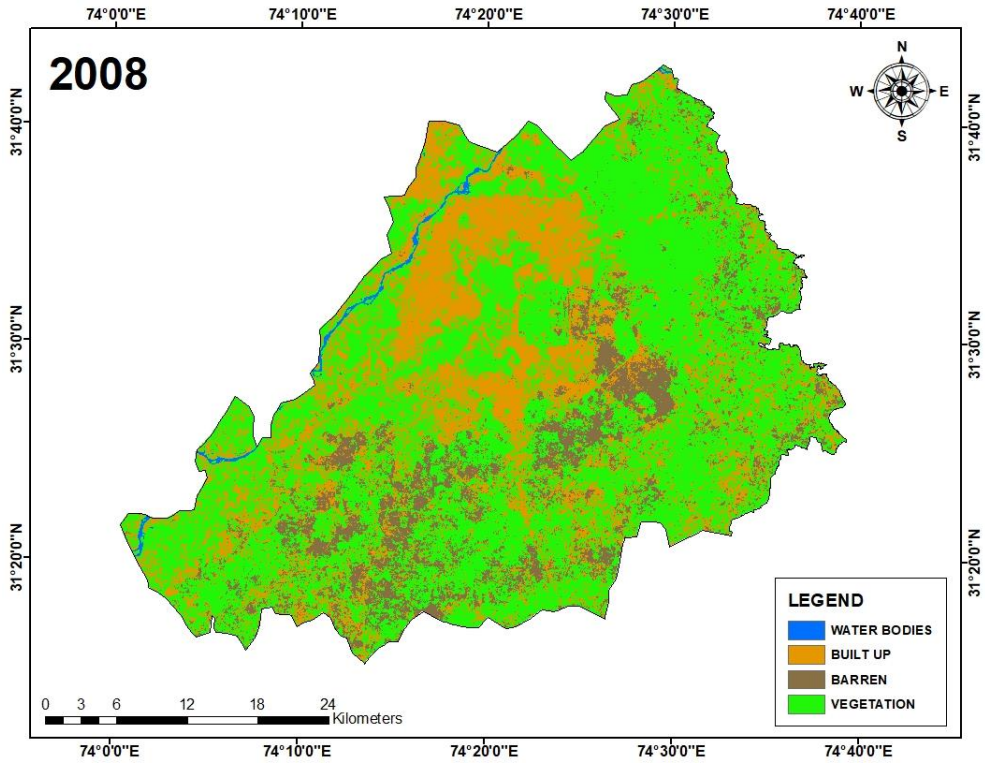**Figure 5.(a)**: Land uses the Landcover for the year 1995
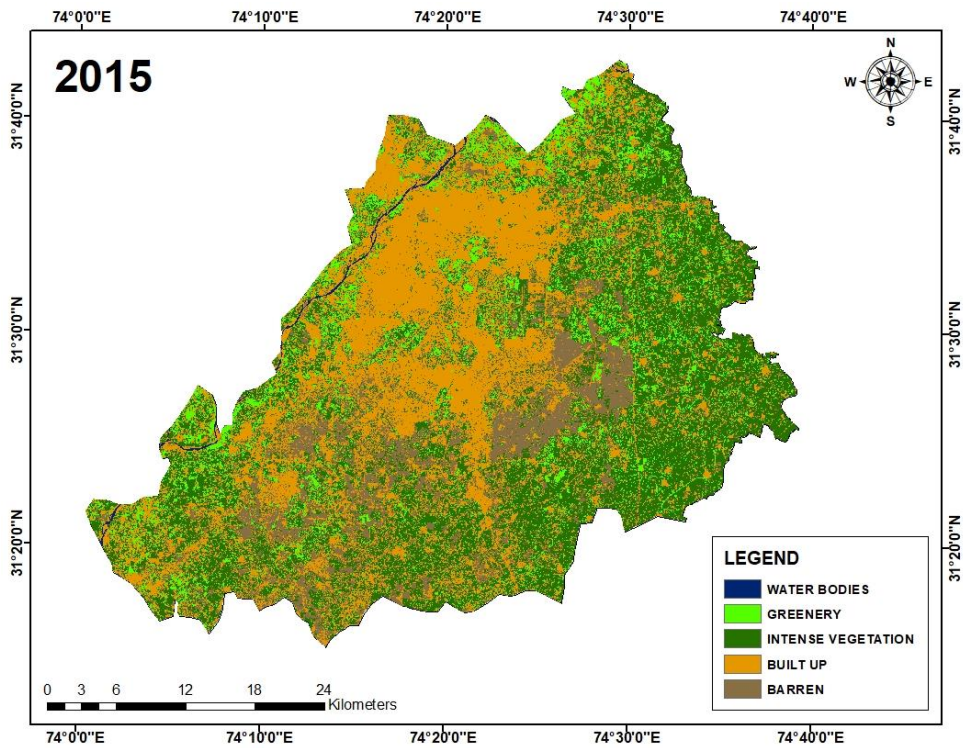
Figure 5(b): Land uses the Landcover for the year 2008
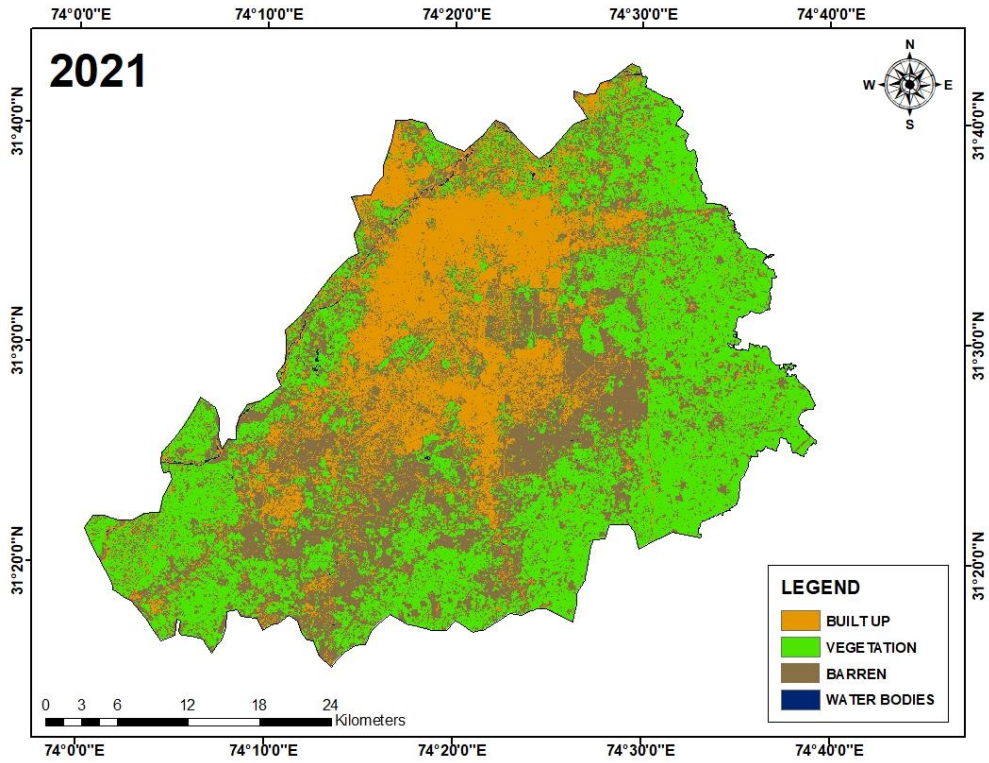

Figure 5(c): Land uses the Landcover for the year 2015

Figure 5(d): Landuse classification results (Area in km²)

Table 2: LULC classes and net change percentage (Area in Acre)

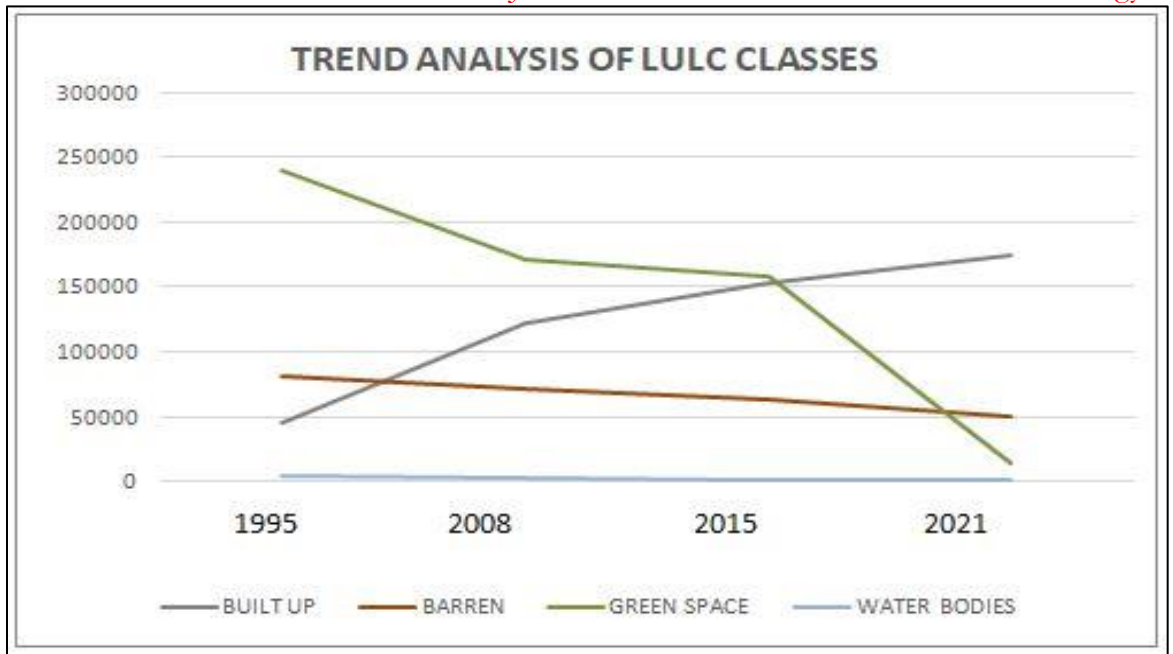| LULC	1995	2008	2015	2021	Net Change
Built Up Area	44640	122246	153875	174667	59.94%
Vegetation	240392	170698	158906	14969	-58.71%
Water Bodies	4052	2271	1617	976	-0.69%
Barren Land	80826	70698	62969	50948	-0.76%

Figure 6. Trend analysis of LULC classes

LULC Change Vs UHI

LULC classification shows for the year 1995, barren (50%), Built-up (11%) and green spaces (38%) water bodies (1%) the respective LST Results are barren (28 - 30°C), Built-up (30 - 33°C), green spaces (25 - 28°C), respectively, wherein 2021 the LULC results displayed barren (15%,), Built-up (43%) and green spaces (41%) water bodies (1%), similarly their respective LST shows built up is > 35°C, barren range 30 -33°C Green Spaces (28 – 30°C).

Comparative results indicate that the UHI effect has become more prominent in areas of rapid urbanization in the study area, and accounted for an increase of 2.1 °C in the surface temperature in Lahore District in the last two decades. With a temperature range of >35⁰C for the whole region in 2021 compared with 1995 >25⁰C. These altered thermal balances in urban spaces; mainly due to unplanned growth results are consistent with [59].

Furthermore, the Spatio-temporal patterns of UHI indicate high values in central and western parts of the city from 1995-to 2008 and an increase in the surroundings in eastwards and southward directions from 2015. This corresponds to the direction of growth in Lahore in the south and southeast directions. Directional restrictions in the northwest are imposed due to the presence of a physical barrier on River Ravi and eastward are due to the Indian border. As construction land had the highest contribution to the UHI effect as compared to barren land in more than two decades (1995-2021). A sharp rise has been observed after 2015 While Urban green spaces including forests, all green fields had intensively negative contributions to the UHI effect as shown (Figure 7). The general lack of vegetation and the low albedo of urban surfaces are Prime Causes of the intensified heat in the Lahore metropolitan.

An additional point also made beyond scope of the current study i.e. a comparative study of thermal bands of Landsat 8 and Landsat 9. the comparative analysis raveals that Landsat 9 is the latest satellite in the Landsat series which mostly replicates its predecessor Landsat 8 in terms of its spectral resolution and bands design . Landsat 9, like Landsat 8, are both radiometrically and geometrically better than earlier generation Landsat [60].However the computation process of LST excuted for Landsat9 (following the same sequential step as in landsat 8 because both have similaty in terms of its thermal charecteristcs). The results (figure 7a) shows Landsat 9 cater with variations and atmospheric corrections more appropriately.
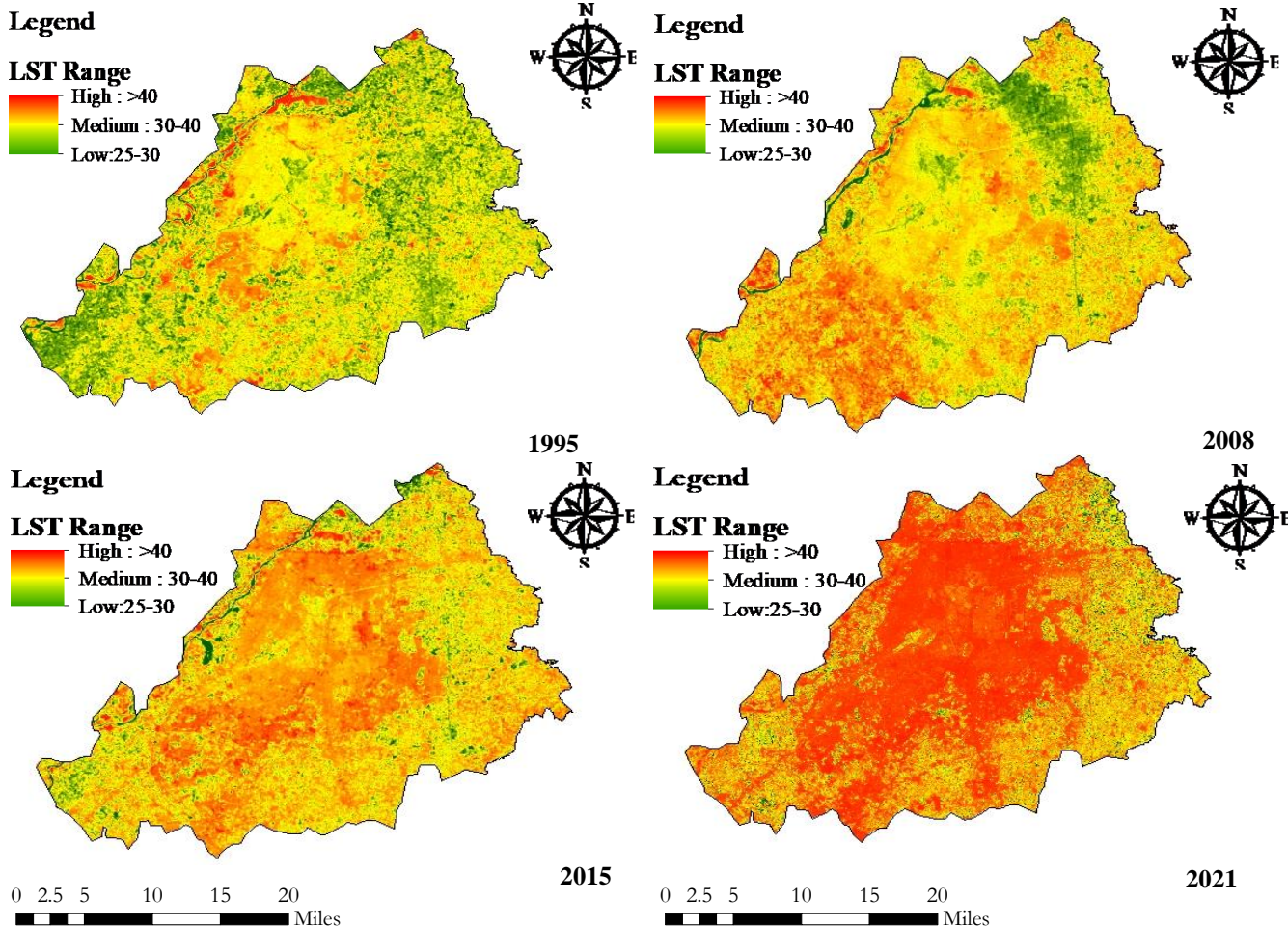

Figure 7. Land surface temperature maps of Lahore for the years 1995-2021
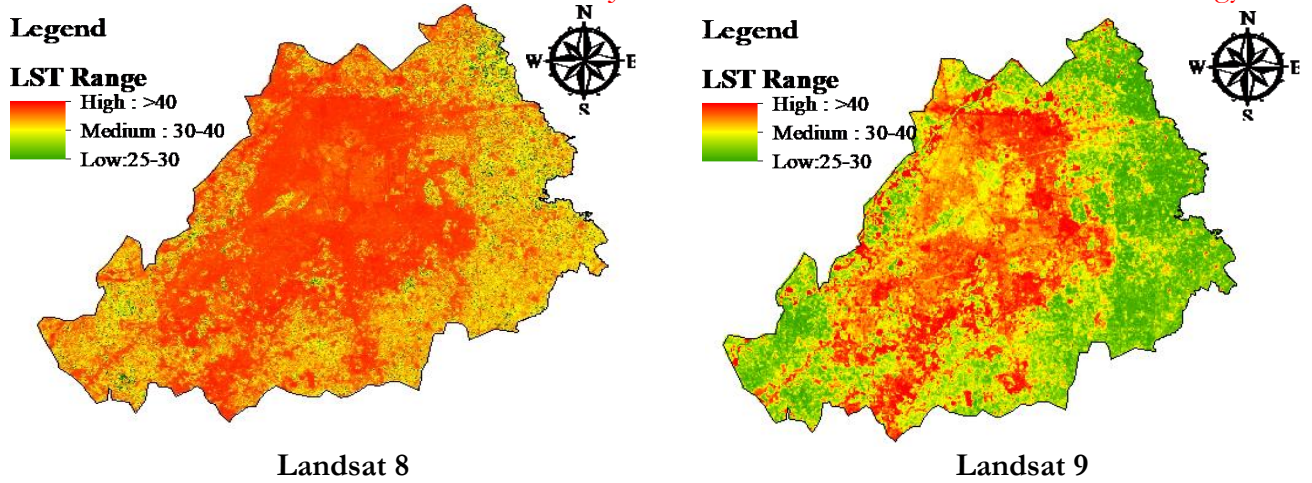
Landsat 8   **Landsat 9**

Figure 7(a) : Land surface temperature maps of Lahore for the years (2021-2022)
(comparative study of thermal bands of Landsat 8 and Landsat 9)
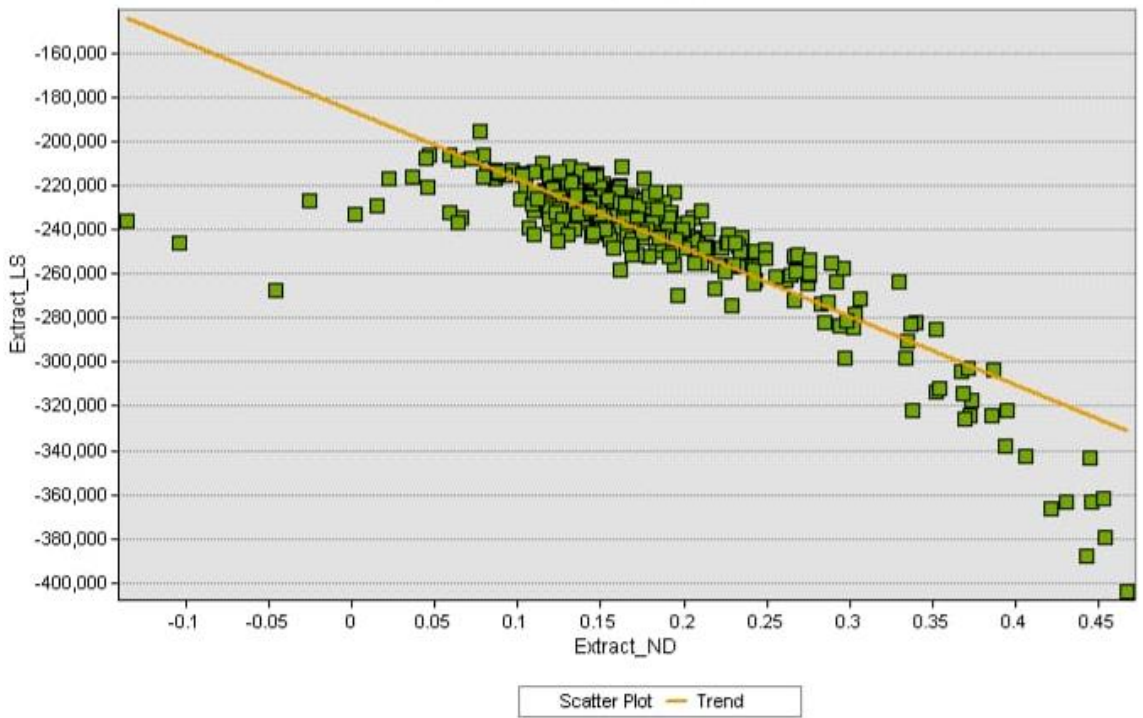
Figure 8a: Correlation map of Land Surface Temperature (LST) and Normalized Difference
Vegetation index (NDVI) for the year 1995
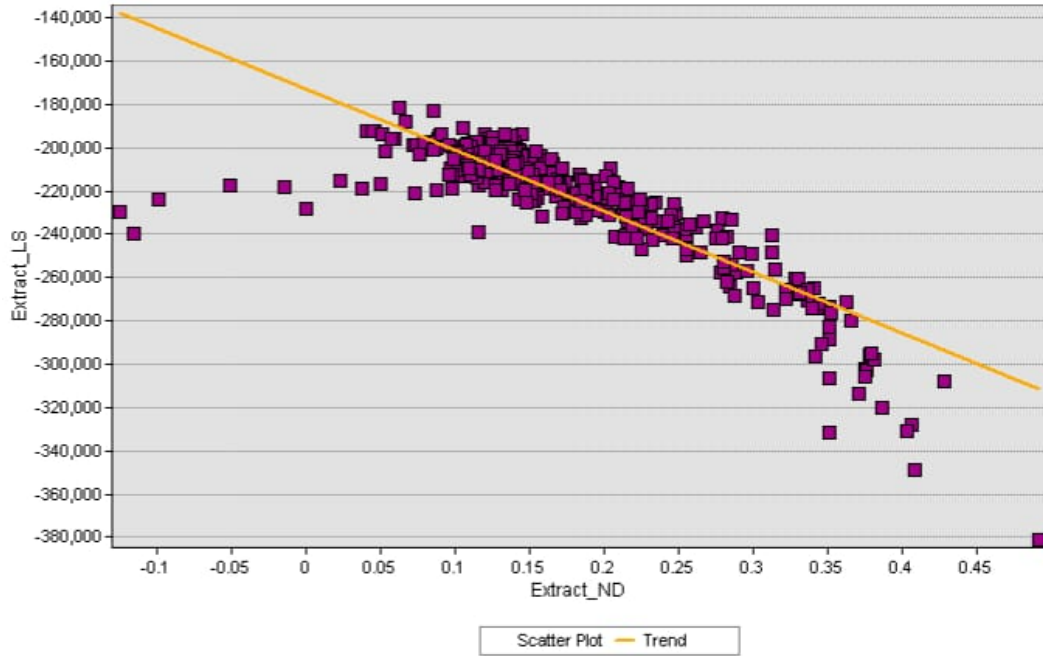
Figure 8b: Correlation map of Land Surface Temperature (LST) and Normalized Difference Vegetation index (NDVI) for the year 2008

Figure 8c: Correlation map of Land Surface Temperature (LST) and Normalized Difference Vegetation index (NDVI) for the year 2015

Figure 8d: Correlation map of Land Surface Temperature (LST) and Normalized Difference Vegetation index (NDVI) for the year 2021

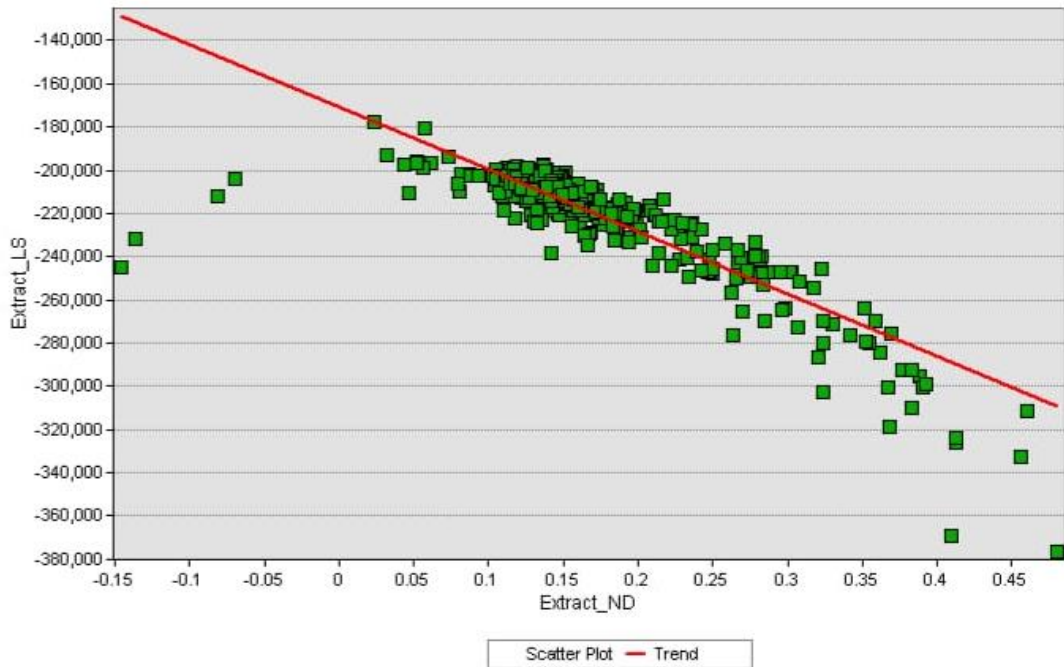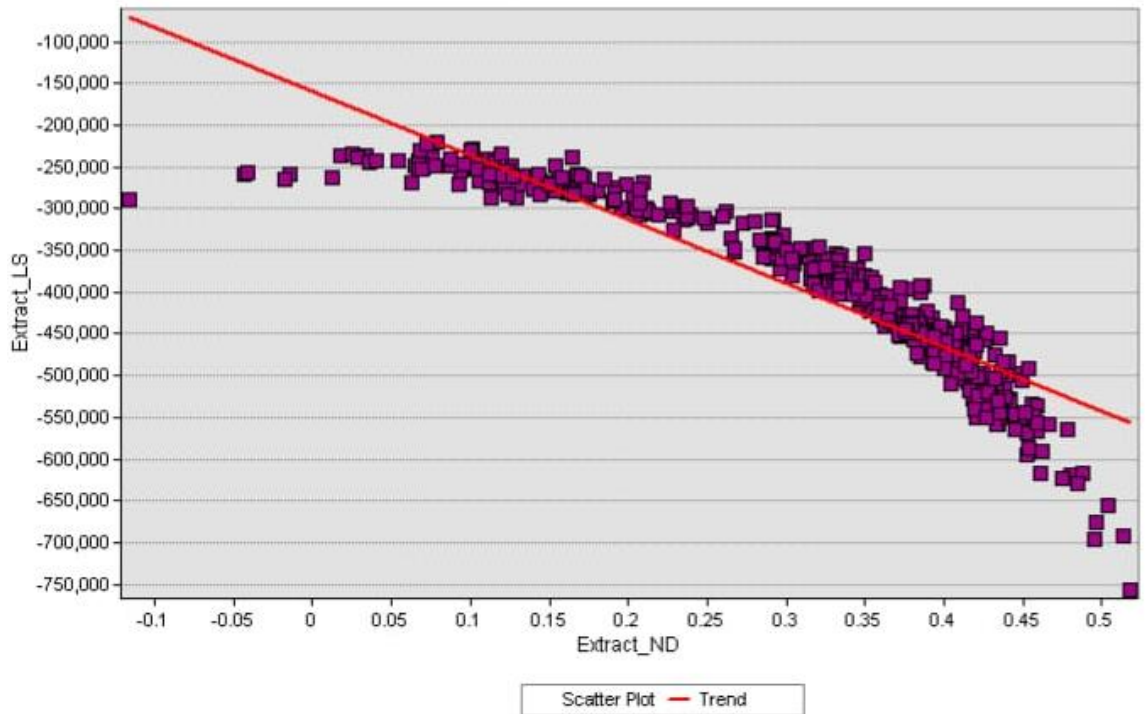A negative correlation is observed between LST and NDVI, with values ranging from 0 to 0.45, indicating a lack of green space and an increase in urbanization. (Figure 8). An alike demonstration has also been established that reduction in vegetation cover is a leading cause of Raised LST which is creating urgency to address proper planning for sustainable urbanization [60], [61]

Population Distribution Vs UHI

Population distribution has a direct link to increasing the potential environmental damage in an area the situation is worsened at low-income levels [62]. The unequal population density is obvious from the map (Figure 9). Open street maps show that Zones like Data Gunjh Baksh, Samnabad, Gulberg, Shalamar, Ravi, and Aziz Bhatti are high-density zones with huge chunks of settlements. The comparison of Land surface maps and papulation density maps shows a positive relationship between land surface temperatures and population density similar to results projected by [63].
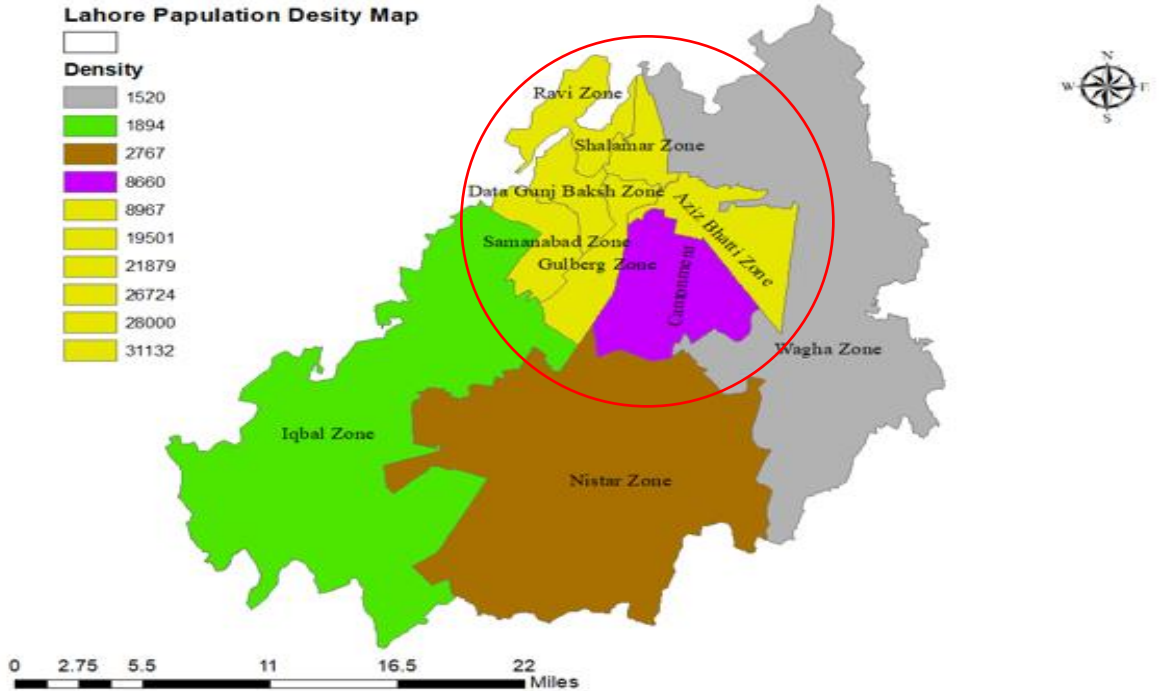
Figure 9: Papulation Density Map of Lahore

Air Quality Vs UHI

The data for Air Quality was extracted from IQ AirVisual website and Punjab Meteorological Department for the year 2021. To find the impact of air quality on urban heat the data has been taken in different zones of Lahore. Specific locations in identified hot spot areas were selected to retrieve data from pre-installed air quality monitors to develop an air quality index map. For this purpose, the data from stations from all zones high density and low-density areas were added on GIS and ranked according to values from good air quality to hazardous situations using Inverse Distance Weightage (IDW) interpolations (Figure 10). The pollutant entered the air from anthropogenic heat release (transport, space and water heating, cooling, etc.) comparisons of results explain that vegetated area and the density have a direct effect on wind and shade distributions. and air pollution; alike demonstration is established by another study in Lahore [62].
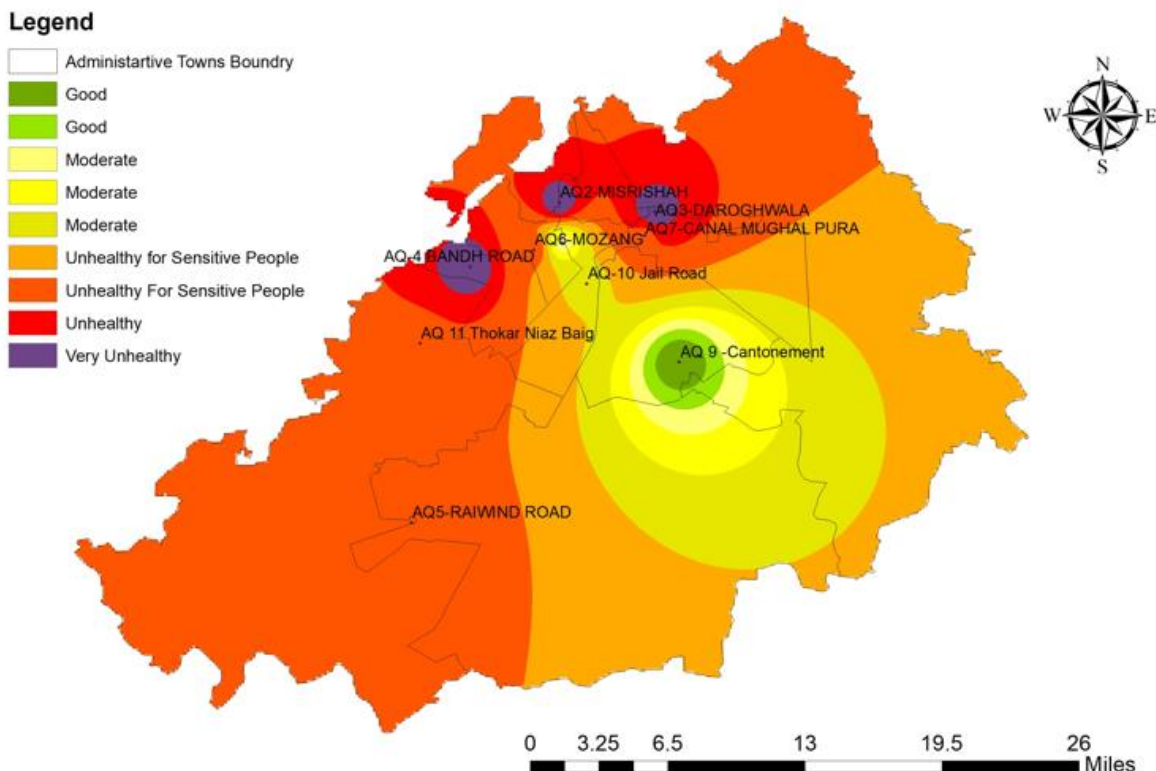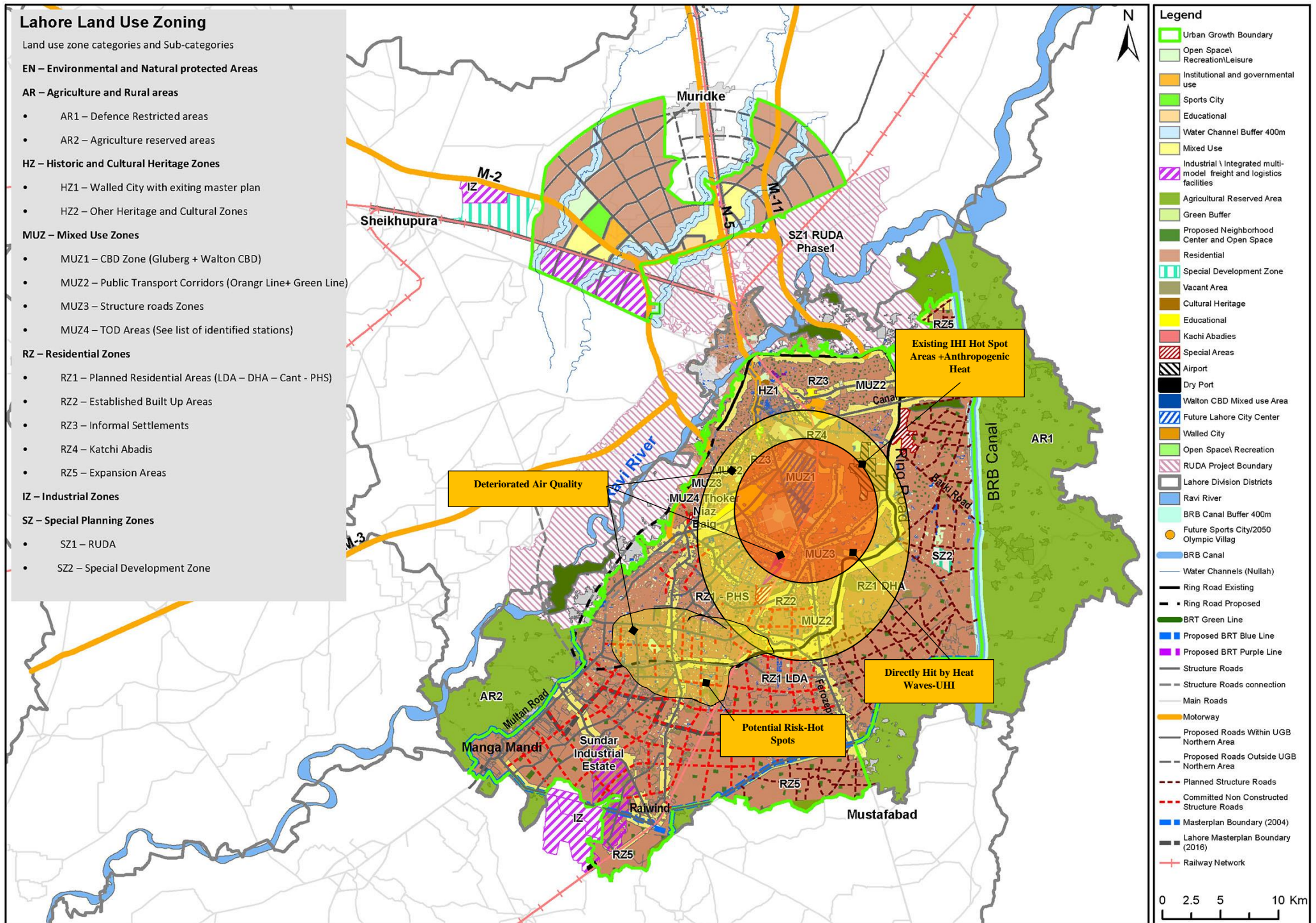
Figure 10: Air Quality Map of Lahore

Comparing the Findings with the Proposed Master Plan of Lahore 2050

Lahore Development Authority Published Lahore Davion master Plan Draft on 17-April 2022. Most of the zones in the residential (RZ= Residential Zones) bloc fall in the UHI hot spot category or potential to turn into hot spots the analysis shows survey through open street maps the possible reason these are the very high population density zones with a huge chunk of settlements combined with a low socio-economic profile. The Suggested zoning in Iqbal Zone and Nishter Zone (RZ5-Extension areas) already affected by heart waves has the potential risk to transform into hotspots if the proposed extension along with current developments occurs at the expense of green spaces. Moreover, the industrial zones (IZ= Industrial Zones) are proposed right next to residential areas without any Green Buffres Zones green belts. The current trend of expansion is associated with urban sprawl and Leapfrog growth development in peripheral areas of these zones. Which is Utilizing the scarce land which was preliminary barren and vegetative areas is affecting thermal (UHI) and environmental conditions (air quality). It signposts that neglecting the UHI in the master plan could enhance urban risks in the future. The drawn comparison can be considered as a baseline to inform the Master plan and other development plans according to the local circumstances of Lahore.

Figure 11: Proposed Master Plan of Lahore 2050 Source: LDA 2022[44]

5.1 Factors Based Mitigation Measures for the Urbanization Heat Island

UHI Determinant Factors	UHI Effect /Impact	Explanation	Suggested UHI Mitigation Measures
Land use Land cover Change **Built-in Environment Surface Material** **Urban structure** **Anthropogenic heat release** **Density** **Air quality/ Speed/Direction**	Enhanced Urban Heat Island (UHI) effect Increased intensity and frequency of heatwave	**Land use Land cover Change** alters the evapotranspiration capacity of the city hence raising the temperature. **Built-in Environment Surface Materials** have an albedo pavement effect which aids in the reflection of solar radiation. **Urban structures** allow different modes of interaction with thermal and solar heat. Material with high albedo pavements would reflect solar radiation and allows cool surface temperatures **Anthropogenic heat and papulation Density Space** heating, manufacturing, transportation, lighting, and human and animal metabolisms Warm the urban atmosphere by conduction, convection, and radiation. **Climate Controls** the air pollution conditions by differences in temperature, rain, pressure, and wind all depending on geographical location, features, and Topographical Direction	**Land Use Planning** Planning at the neighborhood scale, Urban Zoning, and zoning ordinances, restoration, and provision of pervious surfaces (allow water infiltration). **Urban Systems Optimization** Provide Connectivity / Buffering Green Infrastructure /Provision of Air Corridors / Restoration of Green spaces while developing the new areas. **Surface Material**: provision of artificial urban surface covers, Land Surface material with lesser emessitivity e.g. Blended cement systems incorporating industrial wastes in industrial zones. **Urban Structure:** Placement and orientation of buildings, concerning water bodies and the air direction, Green Building designs, Incorporate all green resources at all spatial scales of public property e.g. increase canopy throughout all parks and deciduous trees for winter sun. Along with transportation lines and Power lines bundled to allow improved tree planting. **Energy efficiency**: while deciding about ventilation, lightening and heated or cooling of buildings considerer natural resources first. Passive systems daylighting, natural ventilation, and using the building mass as a thermal storage system are some examples of passive systems. **Urban Lifestyle:** Air Quality, controlled anthropogenic heat release. Light clothing, Idling of automobile engine, etc.
		Promotion of Comprehensive approaches to the Urban Heat Island effect **(Cool urban Environment)**	

Conclusion

The uncertain climatic changes coupled planning raise environmental and social impacts which in turn raise the surface and air temperature in and around the city. The current development practices are creating the potential risk to turn the whole city into a hot spot. Undertaking diagnostic impact assessments of urban development and analyzing the functioning of related institutions is the first step to find out appropriate UHI mitigation strategies. In this regard, the study was relatively successful in identifying the rate of Spatio-temporal dynamics of LULC change. And in gaining an understanding of UHI and its relationship with urban Morphological changes, green spaces, and socio-demographic factors. However, other functional feature of cities of energy and water uses along with emissions from transportation and average building height have their interplay with the other urban features which cast different impacts on the temperature. This laid stresses on the application of a holistic approach when studying the urban heats mechanisms. Furthermore, modeling of urban heat interactions could be improved by using precise and detailed urban planning data, with advanced/high-resolution imageries and ground-level data. The authors foresee that once sufficient datasets from various urban environments around the world have been collected, a Meta-analysis can be accomplished to explain the UHI and its different interactions not only with morphological features and geographical location physical aspects of topography but also with detailed socio-economic considerations to accurately reflect ground realities.

Given the above discussion, the following strategies are recommended for Lahore:

- Development authorities should prioritize and maintain thermal comfort in the city to manage, design, and implement UHI mitigation measures in identified hotspot areas.
- Development authorities should consider city layout design with Greening -based on Land Use/Land Cover and UHI Simulation while preparing the 2050 Master Plan of Lahore.
- The change in the city's UHI profile must be tracked and anticipated to regularize and control the development and devise Policies on land conservation for future development.
- High-resolution multispectral satellite data Along with other freely available applications like OpenStreetMap (OSM) can be used by the city administration to generate and communicate information about the quality of urban green spaces and their accessibility.

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