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The spatiotemporal dynamics of urbanisation and local climate: A case study of Islamabad, Pakistan

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Abstract

Rapid and unplanned urbanisation, together with climate change, are increasingly affecting the local climatic conditions of urban settlements. Spatiotemporal analysis using land use/land cover (LULC), land surface temperature (LST), and local climatic zone (LCZ) assessments have been helpful in understanding the urbanisation characteristics and morphology. Islamabad, the capital and the only planned city of Pakistan, has witnessed a consistent rise in local temperatures, increased built-up areas, and reduced vegetation cover during the past decades. This study explores the spatiotemporal dynamics of LULC, LST, and LCZ in Islamabad using satellite remote sensing data and spectral indices such as Normalized Difference Vegetation Index (NDVI) and Normalized Difference Built-up Index (NDBI). The results indicate a whopping increase in a built-up area in the city (113% during 2013 and 2019). A positive correlation between LST and NDBI, whereas a negative correlation between LST and NDVI clearly indicates how urbanisation (and reduction in vegetation cover) are impacting the local temperatures. Assessment and analysis of LCZs helped to understand the variations and deviations of current LULC from the master plan. It was observed that compact low-rise urban development is the most prevalent. The outcomes of this study are expected to inform the urban planners, climatologists, and policymakers with the knowledge helpful for devising climate-resilient development policies that could reduce thermal stresses in the capital cities.

Keywords: land use/land cover (LULC); local surface temperature (LST); normalized difference built-up index (NDBI); normalized difference vegetation index (NDVI); local climate zone (LCZ)

1. Introduction

Human activities, including social and economic, are the most common drivers of land change (Grimm et al., 2008). With large populations migrating to urban regions, more land is being converted into built infrastructure (residential, commercial, roads, railway networks, airports, and others). Consequently, many of the peri-urban areas are now transforming into dense urban areas (Reiner Jr et al., 2015), resulting in a decrease in green spaces and an increase in impervious surfaces (Oke, 1982). Moreover, rapid urbanisation is also seen as a driving factor exacerbating the impacts of climate change on both natural and built environments (Grimm et al., 2008). If not planned and managed properly, the expansion of urban areas would increase urban climate risks and frequency of extreme weather events (Ching et al., 2018), such as the urban heat island (UHI) effect, heat waves, extreme rainfalls, floods, storms, and droughts. The Fifth Assessment Report (AR5), published by the Intergovernmental Panel on Climate Change (IPCC), states that the global mean temperature has increased the risk associated with extreme events, and this is likely to continue in the future (Pachauri et al., 2014). These circumstances certainly ask for the need to focus on sustainable urban development.

Sustainability is defined as the use of natural resources to meet the needs of the population without compromising or depleting them for future use (WCED, 1987). In 2015, the United Nations (UN) presented 17 Sustainable Development Goals (SDGs), where goals 11 and 13 highlights the need for making cities sustainable and to combat the impacts of climate change (Bebbington and Unerman, 2018). Urban areas are the main drivers of greenhouse gas emissions caused by transportation, industrial production, and energy generation. Additional physical characteristics of an urban area such as form and high-density increase social, environmental, and health risks, making citizens vulnerable to climate change and extreme events – low infrastructure densities, on the other hand, result in increased energy consumption and sprawl (Habitat, 2011).

The climate change phenomenon occurs in all regions worldwide, and its severity has increased during the last two decades. Many developing countries in South Asia, including Pakistan, are witnessing the impacts of climate change in the form of fluctuations in temperature and rainfall patterns (Ali and Erenstein, 2017). The Global Climate Risk Index 2020 established that among the top 10 countries highly vulnerable to the impacts of climate change, seven are from the developing world (Eckstein et al., 2019)– although the contribution of Pakistan to global carbon emissions is negligible, the report ranked Pakistan as the 5th most vulnerable country in the world, with a Climate Risk Index (CRI) of 28.83 which determines the level of vulnerability and exposure to the extreme events, and over 152 reported extreme weather events (Sönke et al., 2020). With rapid urbanisation, poor land use planning and vulnerabilities, urban areas in Pakistan are becoming hotspots for recurrent extreme climatic events and disasters (Rana et al., 2021).

Urban morphology also affects the temperature and thermal stresses, and consequently, the associated impacts on social wellbeing and environmental conditions. The UHI effect is the most common phenomenon. There is a noticeable difference in temperature when a person travels between urban and peri-urban/rural areas – where urban areas feel warmer than the outskirts. Numerous studies have been conducted in several areas around the globe to understand the relationship between urbanisation and UHIs, such as in China (Zhou and Chen, 2018), Vietnam (Son et al., 2017), and India (Kedia et al., 2021). Such analysis, however, requires a wide range of land cover and urban forms to be classified, which largely vary from region to region. The local climate zone (LCZ) system, on the other hand, is arguably a standard methodology that could be applied to identify the diverse climatic and physical conditions of the built environment in any part of the world (Stewart and Oke, 2012).

Land use/land cover (LULC) change is an important parameter to observe urbanisation and associated processes, such as urban sprawl (Al Jarah et al., 2019), urban heat island (Zhou and Chen, 2018), and greenhouse gases emission (Dhakal, 2010). GIS and remote sensing techniques are common and used to ascertain LULC changes in developing countries, e.g., Saudi Arabia (Alqurashi and Kumar, 2019), India (Nath et al., 2021), and Pakistan (Bhatti et al., 2015). Studies have also been carried out to identify the effects of vegetation and built-up on the temperature changes. Land cover indices can assess the spatiotemporal dynamics of the respective land covers and their influence on thermal conditions and UHI. For example, a study conducted in Wuhan, China, used remote sensing data for developing the land cover indices, i.e., Normalized Difference Vegetation Index (NDVI) and Normalized Difference Built-up Index (NDBI), and for land surface temperature (LST) determination (Chen et al., 2013). Similarly, studies have used GIS-based methods to analyse UHIs in Zhengzhou, China (Liu et al., 2020), and Florence and Naples, Italy (Guha et al., 2018). In comparison, other studies have used GIS-based methodologies to develop their respective LCZs for urban areas of the Czech Republic (Geletič and Lehnert, 2016) and the Philippines (Estacio et al., 2019). There are many factors that increase the significance of remote sensing and GIS-based data and methods; remote sensing can provide data for different time periods, whereas GIS could be used to perform spatiotemporal analysis and to predict future patterns by taking into account the historical data, thus assisting in the decision-making process (Hadi et al., 2014).

Local climate zones (LCZs) are mapped regions with uniform surface cover, structure, and human activities with a uniform temperature regime (1-2m) above the ground (Stewart and Oke, 2012). The local climate zoning is useful for carrying out detailed studies on urban form and its relationship with air, water, and temperature. Although initially developed for temperature studies (Stewart and Oke, 2012), the LCZ system is now increasingly used in research on the thermal environment (Kwok et al., 2019), urban morphology (Chen et al., 2019), land surface temperature (Tse et al., 2018), and the UHI (Kotharkar et al., 2019). The LCZs categorise areas into 17 different standard classes based on built-up density and land cover. There are ten classes for the built-up areas such as compact high rise, compact mid-rise, compact low-rise, etc., while the remaining seven are vegetative classes such as dense trees, scattered trees, low plants, etc. (Stewart and Oke, 2012).The LCZ scheme, though primarily developed for urban temperature studies, later became a standard to collect the detailed spatial information about the forms and function of cities under a project named World Urban and Access Portal (WUDAPT) (Bechtel et al., 2015).

The WUDAPT procedure has emerged as a widely used methodology in several studies for mapping LCZs. A study conducted in Alabama, USA, followed the WUDAPT procedure by using the Landsat images from United States Geological Survey (USGS) and training areas from Google Earth (Chieppa et al., 2018). The same methodology was used for Harare, Zimbabwe (Mushore, 2019), and Yogyakarta, Indonesia (Pradhesta et al., 2019). The relationship between LCZs and LST has also been investigated. In Shenzhen, China, the LCZs were compared with the temperature conditions where the data was collected through a mobile survey and static weather stations – the air temperature was interpolated using various interpolation techniques, and regression analysis was performed (Liu et al., 2017). Similarly, another study conducted in the Yangtze River Delta, China, investigated the relationship between LCZ and LST. The LST was classified into five categories using mean and standard deviation and then compared with the LCZ map. The findings showed higher LST in built-up LCZs, and the researchers recommended proper use of urban vegetation and land use planning for future developments (Cai et al., 2018). In another study conducted in San Antonio, Texas, USA, a significant difference was found in land surface temperatures in different LCZs (Zhao, 2018). The air temperature differences among the LCZs were also observed for the urban area of Augsburg, Germany, with varying conditions – the statistical examination of the results indicated clear thermal differences among the LCZs (Beck et al., 2018). For Xi’an, China, the pedestrian level air temperature was observed at multiple sites, and comparisons were made between UHIs and different LCZs (Zhang et al., 2021).

Several other studies with varying methodologies have been carried out for mapping LCZs, but mostly in the developed countries - developing countries, including Pakistan, still lack research in this field. It is imperative to understand the climate dynamics at local scales to formulate appropriate future urban development strategies to mitigate the adverse impacts of climate change on our society and environment. This study focuses on two strands for the purpose of assessment of urbanisation and its associated impacts on local climate in a study area in Pakistan: (1) to analyse the urbanisation characteristics and physical development trends through geospatial analysis of LULC together with LST; and (2) to develop LCZs of the selected area. The integrated approach attempts to establish a link between urban growth and surface temperature through temporal analysis of LULC and LST, while LCZs are assessed in parallel where both the strands of the study are expected to inform the decision-makers, urban planners and climatologists in devising sustainable and climate-resilient urban development plans and policies.

2. Study area

Islamabad, the capital city of Pakistan, was selected as the study area. The city is generally known for its higher standard of living and natural green areas (relative to the rest of the cities of similar size in the country). It is located on the Potohar Plateau between Margalla hills and Rawalpindi district, lying at an elevation of around 460 to 610 meters above mean sea level (see Figure 1b). Islamabad's population, which was around 0.4 million in 1990, has now crossed over 1.2 million. It has the highest literacy rate of 85% (Pakistan Bureau of Statistics, 2016) and the highest human development index of 0.8 in the country(*Pakistan Human Development Index Report*, 2017). The rural population from the nearby peripheries is migrating towards the city in search of better livelihoods and quality of life. With more people coming to the city, more land has been occupied for providing shelter to the rapidly increasing population. The population of the city is increasing exponentially, instigating infrastructural and service provision pressures on the city administration. Consequently, this has spurred several physical development projects and urban expansions in its peripheral areas.

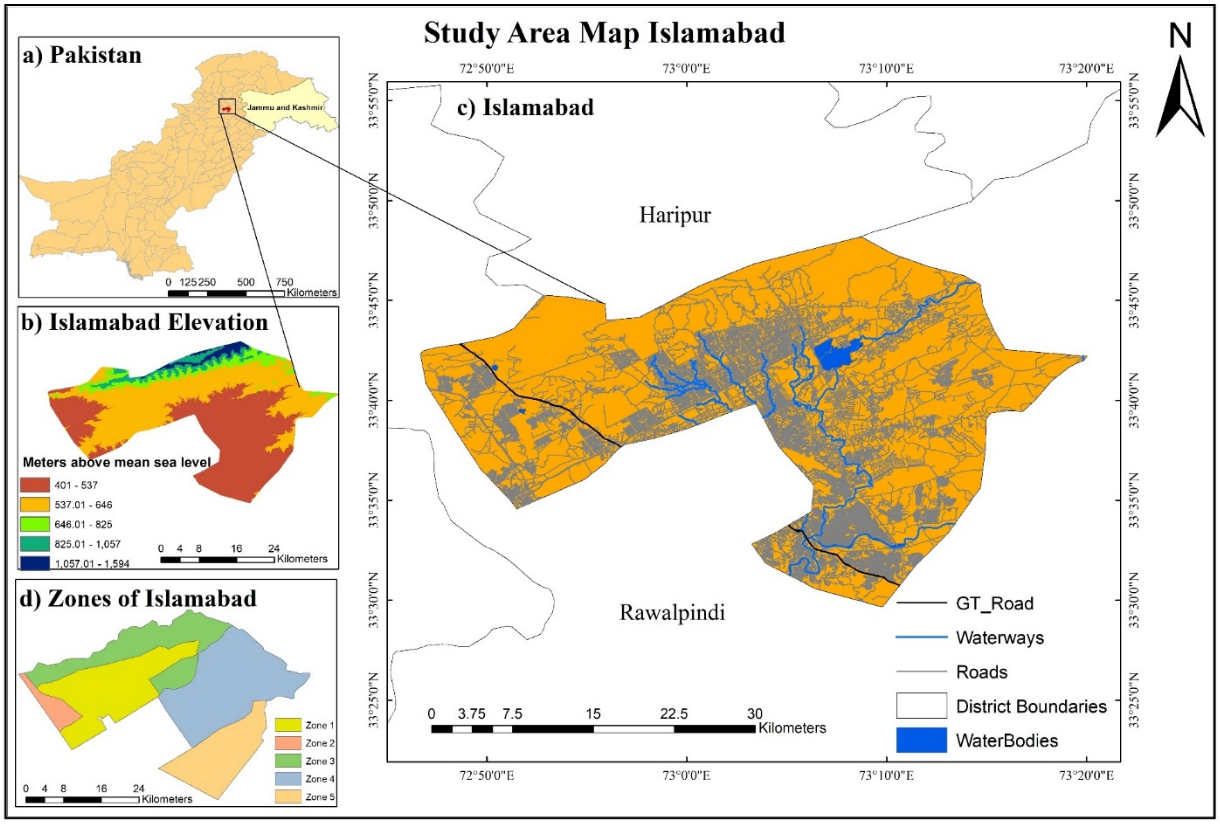

Figure 1 Study area map. a) The administrative boundaries map of Pakistan. b) Elevation map of Islamabad. c) The map of Islamabad showing the roads, waterways, and water bodies, GT-Road within Islamabad boundary and the boundaries of the surrounding districts. d) The map of zones of Islamabad

The city did not evolve like other normal cities in the country – it was purposedly built in 1961 to replace the old capital Karachi, a congested urban area with a relatively high cost of living, challenging climate (Botka, 1995), and limited space for future urban expansion (Associates, 1960). One of the main factors considered while proposing the new capital in the northern part of the country was its geographical proximity to the major road in the country, the Grand Trunk (G.T.) Road (Maria and Imran, 2006). Strategic importance, climate, logistics, defence requirements, aesthetics, and natural beauty were the other primary criteria used for site selection. A commission comprising a group of planning experts was formed, which, after an extensive review of various sites, selected the current location of Islamabad in 1959 (Doxiadis, 1965). After the approval by the concerned Government authorities, the strategy for its planning and development was put into practice.

The urban planning and design of Islamabad are attributed to Constantinos Apostolou Doxiadis, a Greek architect and town planner who gave the principle of dynametropolis (dynamic metropolis). The new capital was envisioned to exhibit an incremental linear growth that would expand unidirectionally towards the southwest (Doxiadis, 1965), whereas the development was restricted towards the North, East, and southeast. The length of the city and its centers would stretch along the Margalla hills (Prentice, 1966). The administrative boundary was termed as Islamabad capital territory (ICT) (Malik and Rajaram, 2017) (Figure 1c), whereas the city centre, termed as a blue area, was placed on the expanding axis with the living spaces alongside the axis (Daechsel, 2013.

In the original master plan given in 1960, for development purposes, the city area was divided into 2 km x 2 km grids (termed as sectors), where these sectors were allocated for various land uses such as residential, commercial, industrial, educational, administrative, diplomatic enclave, national park, and green areas. The master plan since then has undergone several drastic amendments. Some areas of Rawalpindi city were initially planned to be included in the ICT. However, it never happened for the reason that Rawalpindi was a provincial metropolitan of the Punjab province, which for administrative and political reasons, could not be included in the federal (capital) territory (Capital Development Authority Islamabad, 1991). The master plan was thus revised in 1978 to exclude the areas of Rawalpindi from ICT (Botka, 1995).

Later in 1991, the master plan was once again revised by the Capital Development Authority (CDA) with the help of experts from the United Nations Development Programme (UNDP), where Islamabad was divided into five zones (Figure 1d). Zone 1 was designed for housing commercial and administrative land use, and Zone 2 for the private sector, Zone 3 included Margalla Hills National Park, Zone 4 for rural areas, and Zone 5 for private sector development (Maria and Imran, 2006). Another major revision was carried out in 2005 (Peerzada and Naeem, 2019), which allowed the private sector to invest in housing and related facilities resulting in rampant development in the once restricted rural lands. A new commission has now been formulated to develop a new master plan for the city (Tribune, 2020), which has already evolved and expanded to become the ninth-largest city of Pakistan in terms of population.

The exponential population growth is changing the LULC and the climatic conditions of the city. A study analysed the land cover dynamic of Islamabad from 1992 to 2012 and found that the built-up area increased by 213%, while the forest area decreased by 49% (Hassan et al., 2016). The city has also experienced extreme weather conditions in the past decade. It received 620 mm of rainfall in 10 hours in July 2001, the heaviest in Pakistan in the last 100 years (Hameed, 2007). The highest temperature recorded in Islamabad was 46.5°C in June 2005 (Khan et al., 2020). The past trends also indicate that temperature exceeds 40°C in June. The rapidly changing land cover conditions and rising temperatures can lead to changes in the occurrence of extreme events that can affect the living conditions in the city. It is thus important to understand the urbanisation and physical development characteristics of the city to help mitigate the impacts of climate change and to promote climate-resilient urban development.

3. Data and methods

The primary focus of the study is the assessment of urbanisation and its associated impacts on local climate zones in Islamabad. For this purpose, remote sensing data was acquired that was processed to obtain the temporal LULC and LST and to develop LCZs. The data processing and analysis were mainly carried out in ArcMap, Google Earth, and SAGA GIS software. The overall methodology flowchart of the study is shown in Figure 2 – data collection, processing, and analysis methods have been described in the following sections.

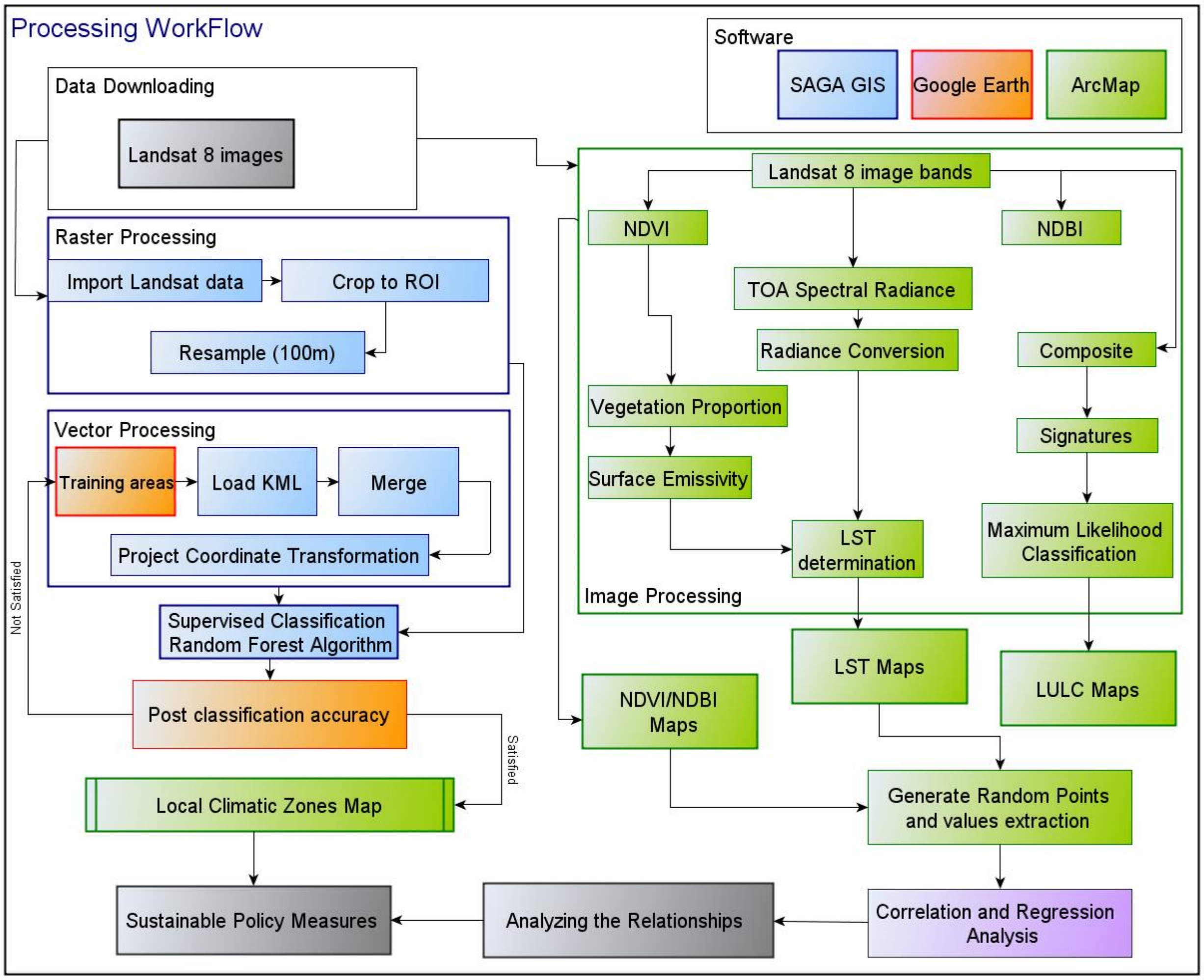

Figure 2 Methodological flowchart of the study
Note: The colour of the boxes represents the software that has been used in the process

3.1 Data collection

Landsat 8 Operational Land Imager (OLI) multispectral and Thermal Infrared Sensor (TIRS) data of 2013 and 2019 was obtained from the USGS Earth Explorer platform (http://earthexplorer.usgs.gov/) (Table 1). The specific details of Landsat data are shown in Table 2. In addition, the satellite images from Google Earth were also used to assist the LCZ classification process.

Table 1 Data sources and its description

Analysis	Data	Source	Resolution
LULC change classification	Landsat 8 Multispectral bands	USGS Earth Explorer	30 m
LST assessment	Landsat 8 Thermal bands	USGS Earth Explorer	100 m
LCZ classification	Landsat 8 / Training areas	USGS Earth Explorer / Google Earth	100 m (resampled)

Table 2 Landsat data information

Analysis	Landsat 8 images
LULC change classification	LC08_L1TP_150037_20130610_20170504_01_T1
	LC08_L1TP_150037_20190627_20190705_01_T1
LST assessment	LC08_L1TP_150037_20130610_20170504_01_T1 (band 10)
	LC08_L1TP_150037_20190627_20190705_01_T1 (band 10)
	LC08_L1TP_150037_20130330_20170505_01_T1 (band 10)
	LC08_L1TP_150037_20190408_20190422_01_T1 (band 10)
LCZ classification	LC08_L1TP_150037_20130330_20170505_01_T1
	LC08_L1TP_150037_20130610_20170504_01_T1
	LC08_L1TP_150037_20131016_20170429_01_T1
	LC08_L1TP_150037_20190408_20190422_01_T1
	LC08_L1TP_150037_20190627_20190705_01_T1
	LC08_L1TP_150037_20191017_20191029_01_T1

Source: Landsat 8 imagery USGS Earth explorer

3.2 Data processing and analysis

The Landsat OLI data acquired for this study was Level 1T (terrain corrected) and thus did not require any additional processing to rectify the spatial displacement errors that occur in the satellite images because of variations in topography. The multispectral bands 1-7 were combined to obtain a composite band image for 2013 and 2019. To observe the seasonal and temporal vegetation changes in the city in summer and spring seasons, the NDVI values were observed for two months of each respective year, 2013 (March, June) and 2019 (April, June). The month of June was selected because it is considered the warmest month in Islamabad. For the year 2013, limited data were available as imageries for the autumn and winter season were mostly covered with clouds, so months of March and April were selected. Different band combinations for natural and false colour composites were used to assist the LULC classification process. For instance, the natural colour band combination of 4 (red), 3 (green), and 2 (blue) was used to get a general idea about the area (vegetation appears green, water is blue to black, and bare soil is light grey to brown colour). Whereas for better identification of the vegetative areas, a band combination of 5 (near Infrared (NIR)), 4 (red), and 3 (green) was used (red colour shows healthy vegetation). For identification of built-up areas, band combination of 7 (shortwave infrared (SWIR) 2), 6 (SWIR 1), 4 (red) was used, while a band combination of 5 (NIR), 6 (SWIR 1), 4 (red) was used for distinguishing the water bodies and land. Using these various band combination, the classes of vegetation, built-up, water, and bare soil were identified, and the signatures were collected accordingly. For every class, 20-25 training samples were collected, and the Maximum Likelihood method of supervised classification was applied using these training samples to obtain the LULC maps of 2013 and 2019. The classification accuracy was measured by cross-comparison of the classified image with the reference image used in the process. Random pixels were selected at various locations to observe the classification results. More training samples were collected for the areas that were not classified properly; the same process was repeated until desired results were obtained.

The NDVI and NDBI were also computed to represent the vegetative and built-up areas in 2013 and 2019, where the outputs were used: (1) to assist compute LST; and (2) to determine their relationship with LST. The NDVI is computed using the NIR and red bands of a satellite image (Table 3) and works on the principle that the chlorophyll in plants absorbs the blue and red spectrum and reflects green – the vegetation reflectance is greatest in the NIR band. The value of NDVI ranges between -1 and 1 for any given pixel in the output image, where sparse vegetation generally ranges between 0.4 and 0.6, and moderate to dense vegetation is shown by pixels exhibiting a value of more than 0.6. Other LULC classes, such as water, built-up, sand, or barren, are shown by values lower than 0.4. NDBI, on the other hand, involves calculations on the SWIR and NIR bands (Table 3), where positive pixel values in the output image potentially represent built-up areas, and negative values indicate features other than the built-up. The Proportion of Vegetation (Pv) was calculated using the min and max values of NDVI, which was then applied to compute the surface emissivity (ε) (Table 3). The surface emissivity was later used to obtain the LST for 2013 and 2019.

Table 3 Image Processing Techniques

Name	Formulae	Equations for Landsat 8
Normalized Difference Vegetation Index (NDVI)	(NIR-Red)/(NIR + Red)	$\frac{(\text{Band } 5 - \text{Band } 4)}{(\text{Band } 5 + \text{Band } 4)}$
Normalized Difference Built-up Index (NDBI)	(SWIR – NIR)/ (SWIR + NIR)	$\frac{(\text{Band } 6 - \text{Band } 5)}{(\text{Band } 6 + \text{Band } 5)}$
Top of the Atmosphere Radiance (L)	ML * Qcal + AL-O_i	0.0003342*”band10”+0.1-0.29
Brightness Temperature (Tb)	(K2 / (ln (K1 / L) + 1)) – 273.15	(1321.0789/Ln(774.8853/"L" + 1)) - 273.15
Proportion of Vegetation (Pv)	((NDVI-NDVImin)/(NDVImaxz-NDVImin))2	Square(("NDVI" + 1)/(1 + 1))
Surface Emissivity (ε)	0.004 * Pv + 0.986	0.004 * Pv + 0.986
Land Surface Temperature (LST)	Tb/[1+(*Tb/c2)*ln(ε)]	"Tb" / (1 + (10.8 * "Tb" / 14388) * Ln("ε "))

The Landsat 8 TIRS acquires thermal data in two bands (10 and 11); however, considering the recommendation by the USGS, band 11 was not used in this study as it has a larger calibration uncertainty (Avdan and Jovanovska, 2016) – the only band 10 was processed to obtain LST for 2013 and 2019. The Top of the Atmosphere (ToA) radiance (L) and brightness temperature (T_b) from radiance were calculated from band 10 (Table 3). "L" was computed by the multiplicative rescaling (ML) factor and the additive rescaling factor (AL), where both are band-specific and were obtained from the corresponding metadata files of the satellite images (Table 3). The correction value of 0.29 specific to band 10 was used. To compute the brightness temperature (T_b), the values of band-specific thermal conversion constant for K1 and K2 were applied, which were obtained from the corresponding metadata files of the satellite images. Using the surface emissivity (ε) (obtained through NDVI and Pv, see Table 3) and brightness temperature (T_b), the LST was determined.

The relationships between NDVI, NDBI, and LST were then examined using correlation and regression analysis through scatterplots and trendlines. For this purpose, random points were generated, and the corresponding values for NDVI, NDBI, and LST were extracted. Trendline tool in MS Excel was applied for regression analysis and to identify the correlation between the data points – a linear fit was used to identify the best fit. The R^2 values show the variance, and its square root gives the values of correlation. To counter check the results, Pearson's correlation function was also used to identify the value of the correlation.

To classify the study area into LCZs, a standard WUDAPT procedure was followed. The process involved preparing the training areas to classify the Landsat images of 2013 and 2019 into 16 LCZ classes such as, for example, LCZ 2 (compact midrise), LCZ 3 (compact low rise), LCZ 9 (sparsely built), LCZ 10 (heavy industry), LCZ C (bush, scrubs), and others. The Landsat data was first imported into SAGA GIS software, where it was cropped according to the region of interest (ROI) and then resampled to 100m resolution. The spatial scale of analysis may vary depending upon the classes and cities. However, the default value of 100m was used for mapping LCZ in this instance (Bechtel et al., 2015). The training areas were then prepared through Google Earth (due to the availability of high spatial resolution images on the platform that helped identify a variety of samples for the corresponding LCZ classes), and the required sample areas were digitised. For the preparation of training samples, a sample file was downloaded from the WUDAPT website with classes – changes were made to it according to the study requirements, and the data was then uploaded to Google Earth for the collection of respective training samples. Depending upon the knowledge, training samples of each class were digitized under their respective names and then saved as a KML file. The KML files were then imported into SAGA GIS, where supervised classification was carried out using the Random Forest algorithm, as suggested by WUDAPT, to obtain the LCZ classification map of the study area.

The post-classification accuracy was examined by cross-comparison of the LCZ output maps overlaid on Google Earth images. For this, various locations (pixels) were randomly selected, and the reference data from Google Earth and the LCZ maps were compared. More training samples were taken for the areas that were not classified correctly, and the process was repeated until satisfactory results were obtained.

4. Results and discussion

4.1 Urbanisation and local temperature

4.1.1 Land use / land cover change

Satellite imageries of 2013 and 2019 were analysed to determine the LULC change in Islamabad – the LULC maps indicate a decrease in green areas during this period (see Figure 3 and Table 4). The green areas reduced by around 33%, while the built-up area increased drastically by around 113% during the span of just 6 years. These figures indicate the alarming rate at which physical development is taking place in the city.

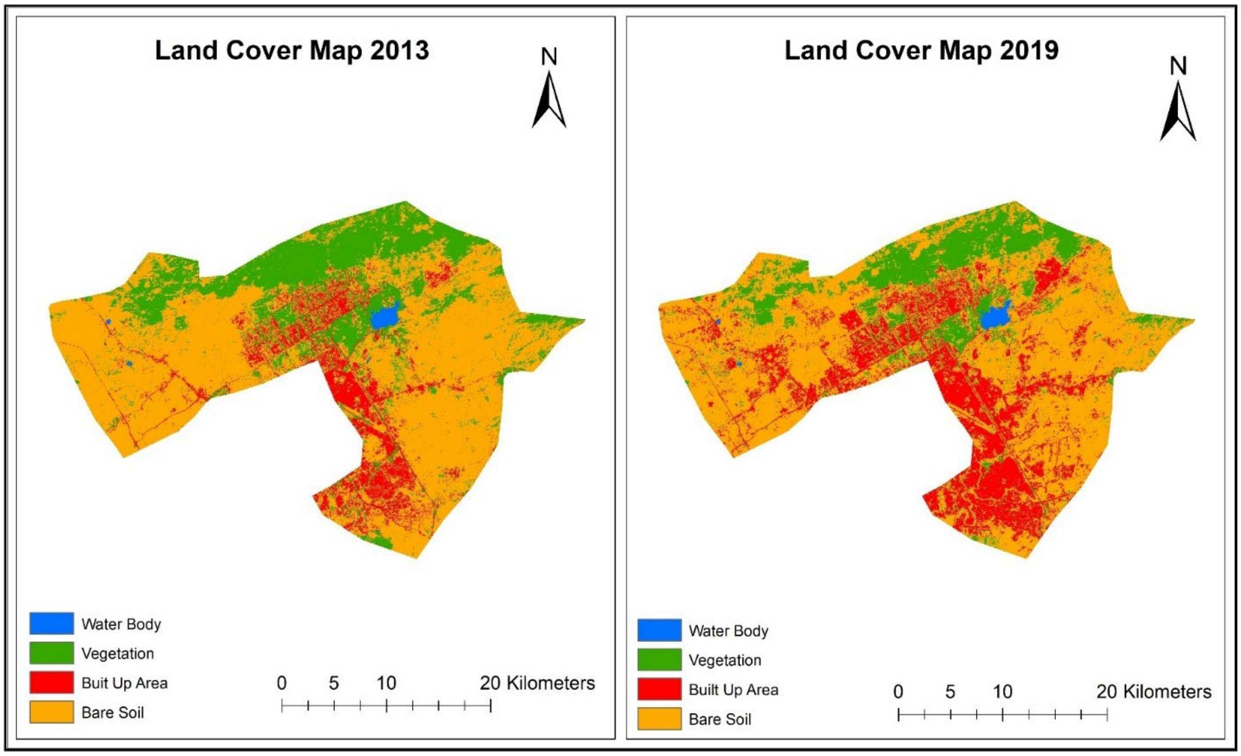

Figure 3 Land cover map of Islamabad of the year 2013 and 2019

Table 4 LULC change in Islamabad during 2013-2019

	Area (km^2)		**Percentage (%)**		**Percentage change**
	2013	*2019*	*2013*	*2019*	
Built up area	87.66	187.11	10.36	22.12	113.46% increase
Vegetation	204.17	135.98	24.14	16.08	33.39% decrease
Bare soil	548.32	517.18	64.85	61.17	5.67% decrease
Water body	5.31	5.17	0.62	0.61	2.57% decrease
Total	845.46	845.46	100	100	

Bare soil or open areas also decreased during this time period, indicating that the landscape is continuously changing. The infrastructure development is happening at the expense of both vegetation and open areas. The spatial comparison of the maps reveals that the urban growth is taking place mainly in the south and southwest direction – the master plan (1991) of the city also envisioned future development in this direction. However, the reduction of vegetative cover, especially in Zone 3 (conservation/protected zone) Margalla hills national park and Rawal Lake, is a gross violation of the master plan. Therefore, a planned and controlled physical expansion is needed to conserve the green areas of the city.

4.1.2 Normalized difference vegetation and built-up indices

The NDVI analysis has been done to confirm the land cover changes and to observe their relationship with LST. To observe the seasonal and temporal vegetation changes seasons, the changes in the NDVI values were observed for two months of each respective year, 2013 (March, June) and 2019 (April, June). Overall, the mean NDVI value decreased from 0.25 (2013) to 0.23 (2019) (see Table 5). The maximum value of NDVI in the year 2013 was 0.55, while in 2019, it was 0.59. An increase in the maximum value was also observed for June. Figure 4 shows the spatial variations in the NDVI values for selected years – vegetation cover decreased (shown in colour tones of green), while non-vegetative areas increased (shown in colour tones from yellow to red). Zones 2 and 4 clearly exhibited a decrease in vegetation cover. According to the master plan, Zone 4 was designated for rural areas, while zone 2 was for private sector development. However, a dramatic decrease in the vegetative cover and increasing built-up land was observed, which can be attributed to the physical development of new private housing schemes in these zones. The values of NDVI were high and fairly consistent in Margalla hills for both years, indicating a somewhat stable vegetation condition in this area.

The NDBI was used to compare the non-built-up areas such as vegetation, water bodies, and bare land. This was done to counter-check the findings of the LULC and NDVI change analysis. It was calculated for four time periods (March 2013, June 2013, April 2019, and June 2019). The lowest value of NDBI was observed in the region of Margalla hills for all four time periods (Table 5). Figure 4 shows the spatiotemporal changes in the NDBI values for Islamabad. The green shaded area (non-built-up) was quite high in 2013 in zone 4, which reduced significantly by April 2019 – this shows a dramatic change in the land cover in this region, which is supported by the results of the LULC and NDVI maps which indicate a reduction in vegetation cover in this area.

4.1.3 Land surface temperature

Rapid urbanisation and built environment are among the leading causes of increasing urban temperatures (Ongoma et al., 2016). Urban development impacts the temperature in urban areas; for instance, the areas with dense infrastructure mostly have higher LST values, whereas those exhibiting more vegetative cover have low LST values (Tse et al., 2018). Urbanisation and land cover change subsequently impact the urban temperature and causes an increase in thermal stresses. The LST maps were prepared, and temperature ranges were defined to compare the changes in the LST conditions over the selected time period. The imagery of April was not available for 2013, so the imagery of the end of March has been used for the year 2013. By comparing both the LST maps for March and April, it can be seen that most of the areas, which were 20-25^{o}C range in the year 2013, exhibited a temperature range of 25.1-30^{o}C in 2019 primarily due to the change in LULC (increase in the built-up area). A large proportion of city areas fall in a higher temperature range. The descriptive statistics of LST have been provided in Table 5. The mean temperature was around 22^{o}C in March 2013, which reached 26^{o}C in April 2019. Also, the maximum temperature reached 30^{o}C in March 2013, while it crossed 39^{o}C in April 2019. To cross-check, the LST was also determined for another month, i.e., June. In 2013, the maximum temperature attained in June was around 37 to 39^{o}C, mainly observed in the outskirts of the city (mostly bare land). However, the same temperature range was observed in the city centre in 2019. The temperature ranges in June 2013 placed most of the areas in 30 to 35 ^{o}C, while in the year 2019, the majority of city areas fell in the range of 35.1^{o}C to 40^{o}C. The maximum temperature difference between the two timespans was around 5^{o}C. The maps clearly show the areas belonging to the average temperature range in 2013 exhibited higher than average temperatures in 2019.

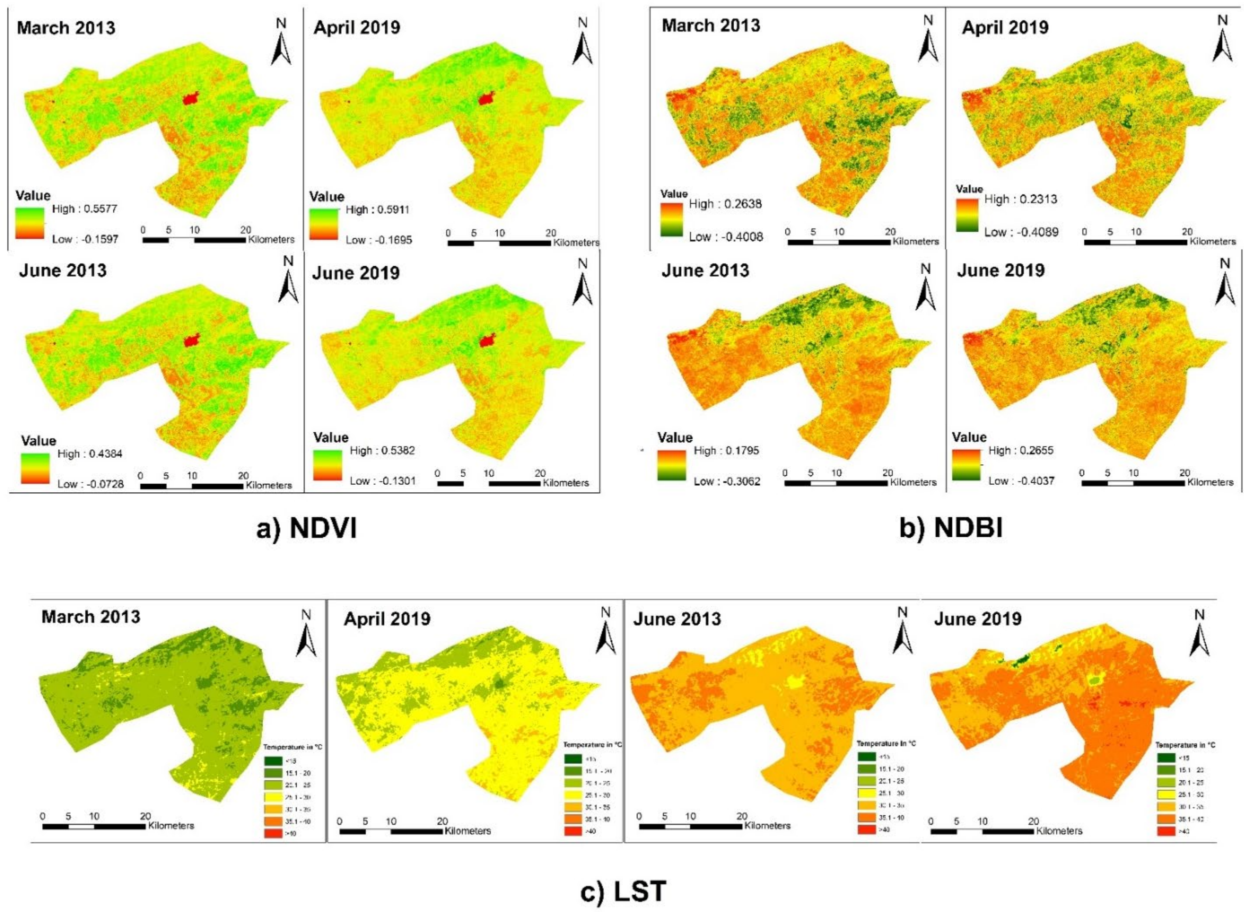

Figure 4 a) Normalized difference vegetation index (NDVI) map of Islamabad of the year 2013 and 2019, b) Normalized difference built-up index map (NDBI) of Islamabad of the year 2013 and 2019, c) Land surface temperature map of Islamabad of the year 2013 and 2019

Table 5 Descriptive statistics of NDVI, NDBI, and LST for the years 2013 and 2019

Time Period	NDVI				NDBI				LST			
	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
March 2013	-0.16	0.56	0.25	0.09	-0.40	0.26	-0.09	0.08	12.69	30.20	21.97	1.76
June 2013	-0.07	0.43	0.16	0.05	-0.30	0.17	-0.01	0.04	24.93	38.12	33.71	1.66
April 2019	-0.17	0.59	0.23	0.09	-0.40	0.23	-0.07	0.07	16.28	39.08	26.40	2.23
June 2019	-0.13	0.53	0.17	0.06	-0.40	0.26	-0.02	0.05	10.01	43.65	35.23	3.11

4.1.4 Impacts of urbanisation on land surface temperature

The reduction in the vegetative cover and increase in the built-up areas is evident from the land cover maps (Figure 3). The built-up area increased by 113.46% from 2013 to 2019, while the vegetative cover decreased by 33.39% during the same period. The bare land, as well as the area occupied by water bodies, also decreased. These changes can also be observed in the NDVI and NDBI maps (Figure 4). In terms of temperature variations, the mean in June 2013 was 33.71 ^{o}C, while it was 35.23 ^{o}C in 2019 (Table 5). Thus, it can be hypothesized that LST increases with the increase in built-up and bare land and decreases with the increase in vegetative cover and water bodies. To further confirm the hypothesis, a correlation analysis was performed between NDVI/LST and NDBI/LST.

NDVI alone can be used to identify the increase or decrease in the vegetative cover, while its use with the LST can help to determine if the temperature changes are linked to the changing land cover conditions. The correlation and regression analysis revealed that LST had a negative relationship with NDVI (Figure 5). The R^2 is defined as the regression coefficient. The scatterplot between NDVI and LST has been plotted for four timespans (i.e., March 2013, April 2019, June 2013, and June 2019); the regression coefficients have also been displayed on the graphs calculated from the linear regression trendline. The R^2 values were 0.280, 0.202, 0.084, 0.0006 for March 2013, April 2019, June 2013 and June 2019, respectively. The Pearson's correlation was also calculated between the two variables for all time frames, March 2013, April 2019, June 2013, June 2019), and it came out to be -0.529, - 0.450, - 0.290, and -0.0244, respectively (the negative sign indicates an inverse relationship between NDVI and LST).

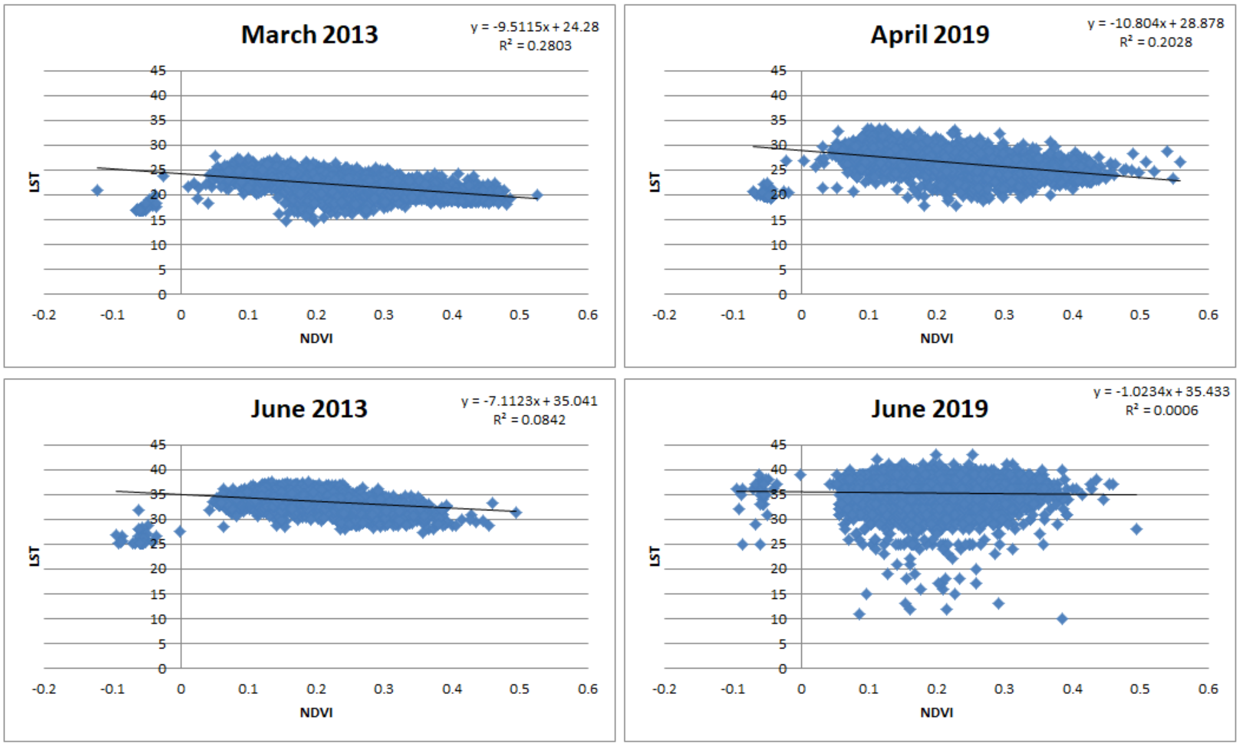

Figure 5 Relationships between NDVI and LST (2013 and 2019)

To further confirm the relationship between NDVI and LST, NDBI values were plotted against the LST, and correlation was calculated. The results indicated R^2 values of 0.421, 0.279, 0.521, 0.242 and the Pearson's correlation values of 0.648, 0.528, 0.721, 0.492 for March 2013, April 2019, June 2013 and June 2019, respectively. The higher correlation values show that LST has a strong positive correlation with NDBI (Figure 6). From the above findings, it can be seen that LST increases with an increase in the built-up area and bare land, while it decreases with an increase in vegetative cover. The relationship observed between NDBI and LST is stronger as compared to LST and NDVI.

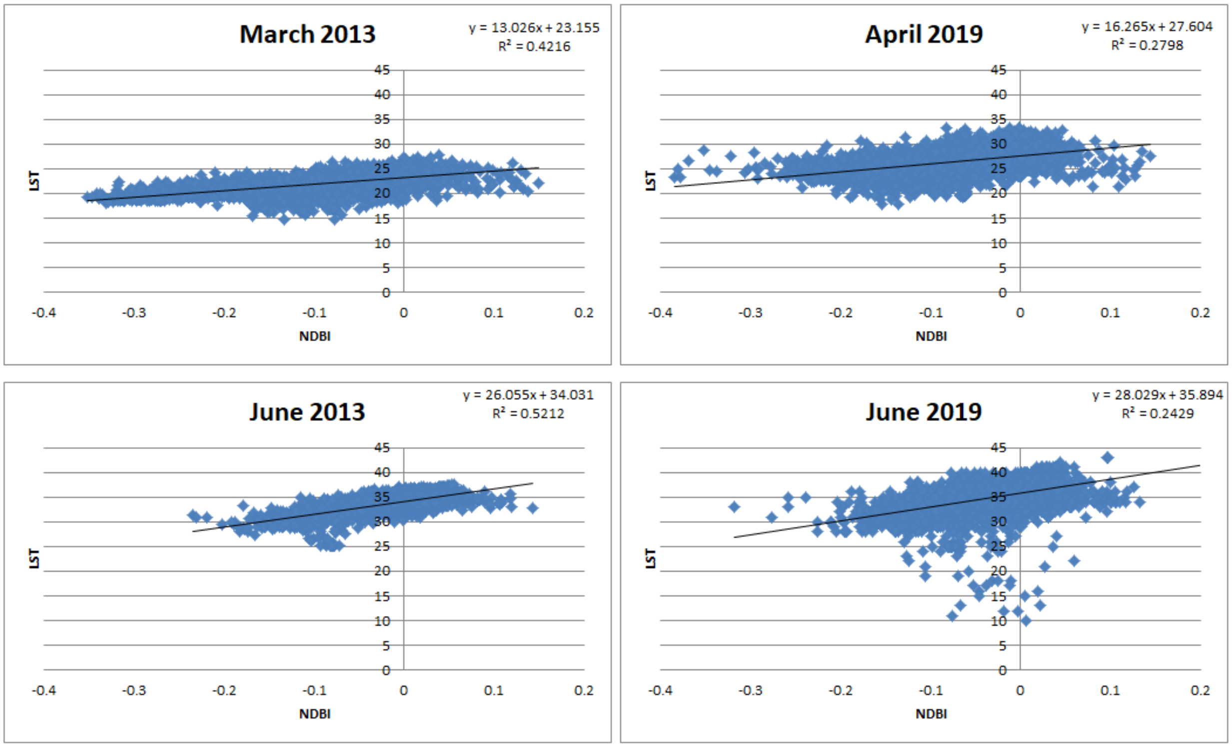

Figure 6 Relationships between NDBI and LST (2013 and 2019)

Overall, the results clearly show that the overall temperature of the city has increased. A large portion of the city now belongs to the high-temperature range, implying high climate/heatwave hazardous areas. These results call for incorporating climate-resilient development and planning strategies in master plan revisions to avert the serious impacts of climate change and rapid urbanisation on humans and the environment in the future.

4.2 Local climate zones

The study area was classified into LCZs to analyse the type of built-up, open or compact and high-rise or low-rise, that affects the thermal conditions of the area. The satellite view of sample locations of these zones in Islamabad is shown in Figure 7 (Google Earth snippets) that helps to understand the variation in these classified regions. From the LCZ maps produced for the study area, the type of built-up or development can be easily identified (Figures 8 and 9). The LCZ scheme can identify 17 distinct classes – the first class (LCZ 1), i.e., compact high-rise, was not found in the study area (for both 2013 and 2019), and therefore, only 16 classes were mapped.

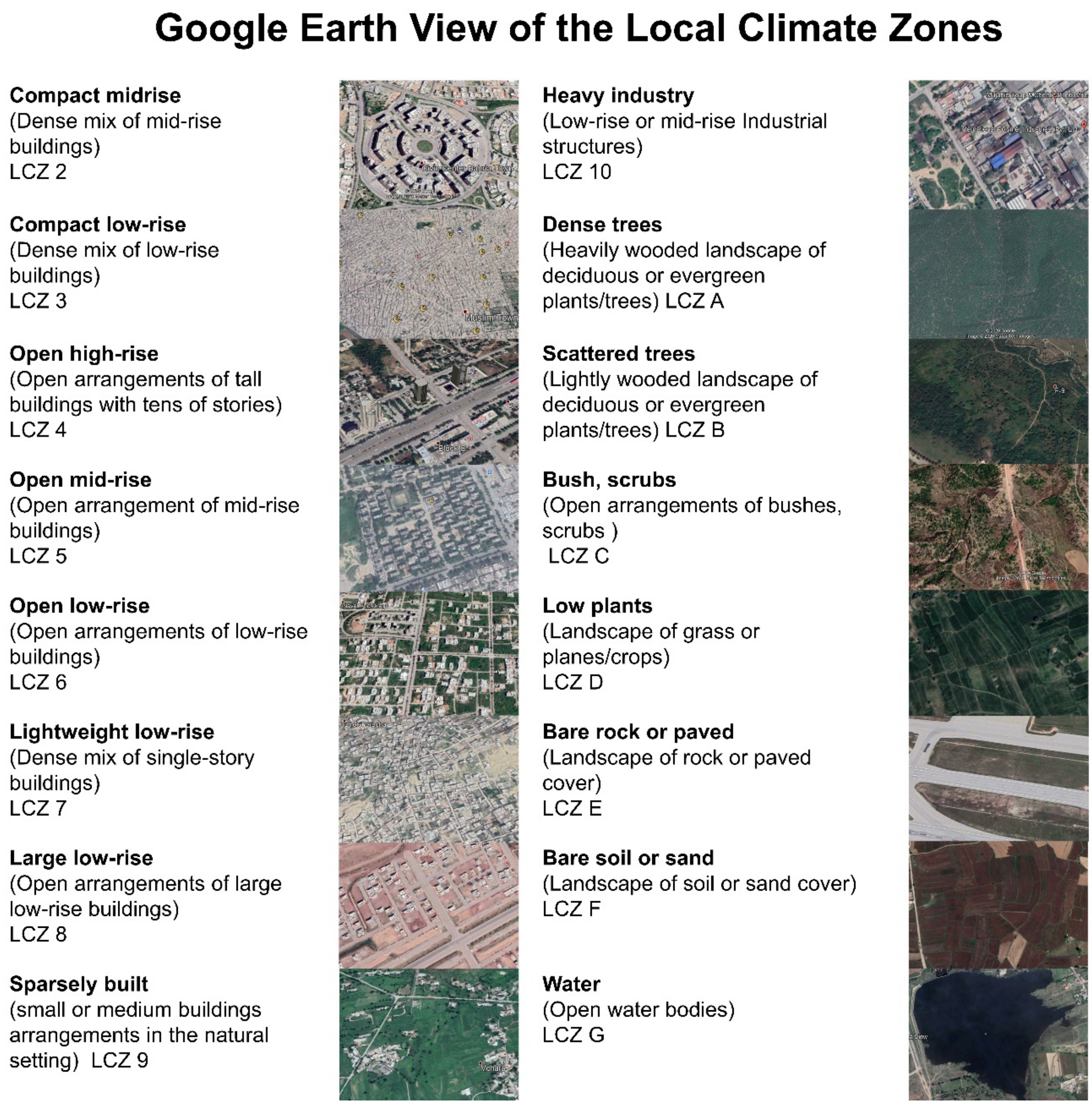

Figure 7 Visual representation of the local climate zones of Islamabad from Google Earth

The LCZ map of 2013 showed that most of the areas in the outskirts fall in the category of LCZ F (bare soil or sand) (Figure 8). The dense vegetative cover (LCZ A) can be observed in the areas of Margalla hills and F-9 Park. LCZ 2, the compact mid-rise, was present mainly in Zone 5 of the city – this zone is primarily used by the private sector housing development. There has been a lot of compact low-rise development, i.e., LCZ 3 in the south direction in Zone 4 of Islamabad that is mainly assigned for rural areas. A few open high-rise buildings, LCZ 4, were present in the 'blue area' (commercial zone of Islamabad). LCZ 5, i.e., open mid-rise development, was present in sector G-9 (Karachi company area) in Zone 2. The most dominant class was LCZ 6, i.e., open-low rise followed by compact low-rise, i.e., LCZ 3. The peripheries showed sparsely built settlements, i.e., LCZ 8 and 9, whereas the heavy industrial zone occupied a small area. LCZ A, i.e., dense trees, enveloped the region of Margalla Hills. There was also compact low-rise development in some parts of Zone 3 that are conserved for the National Park. LCZ G, i.e., water, mainly showed the Rawal Lake.

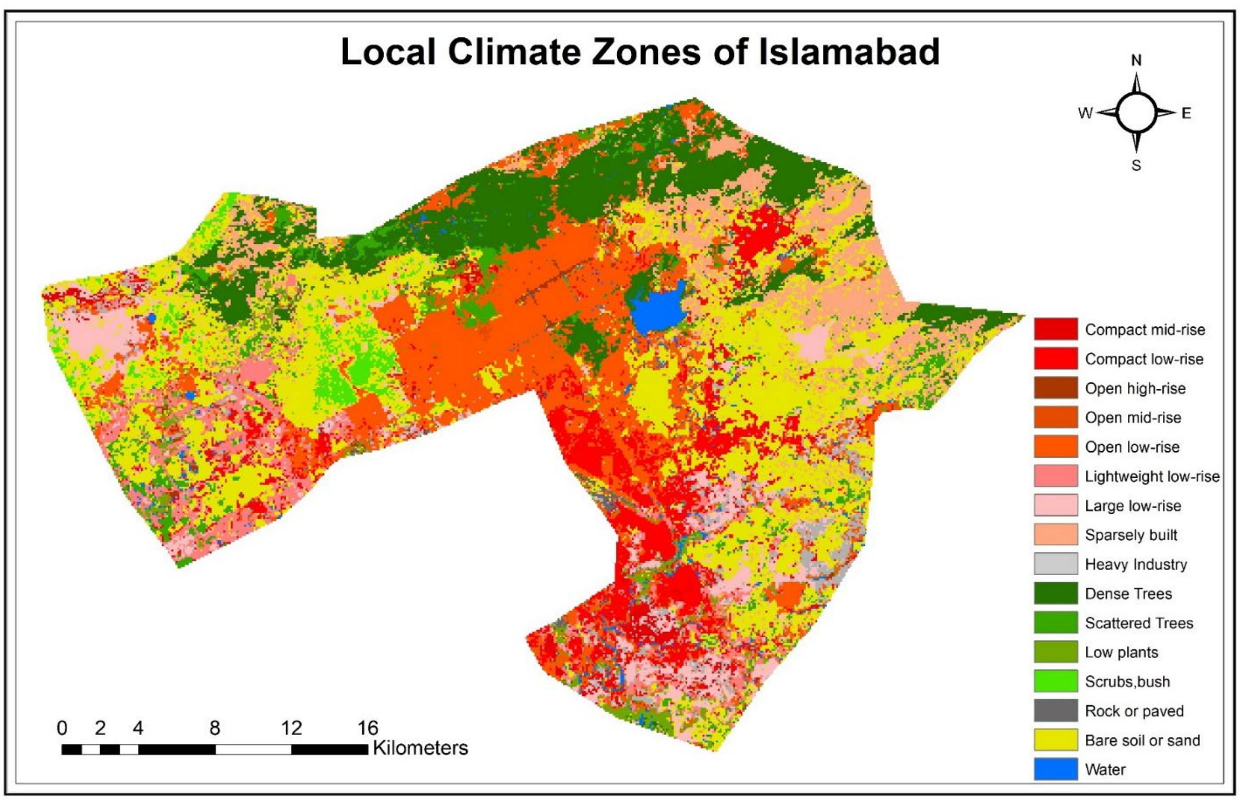

Figure 8 Local climate zones Map of Islamabad 2013

From the LCZ map of 2019, the changes can be observed in the dense vegetative cover (LCZ A) (Figure 9). In the area of 'F-9 Park', the dense vegetation cover has been reduced. An increase in LCZ 3 (compact low-rise) and LCZ 6 (Open low-rise) categories was also evident. The compact low rise developments have been increased, and it can be seen clearly in the area of 'Bhara Kahu'. The low plants (LCZ C) and the bush/scrubs (LCZ D) present in the west direction have also been reduced. In the areas of Zone 4 of the master plan, some of the sparsely built settlements (LCZ 9) were converted into open low rise developments (LCZ 6) during 2013 and 2019.

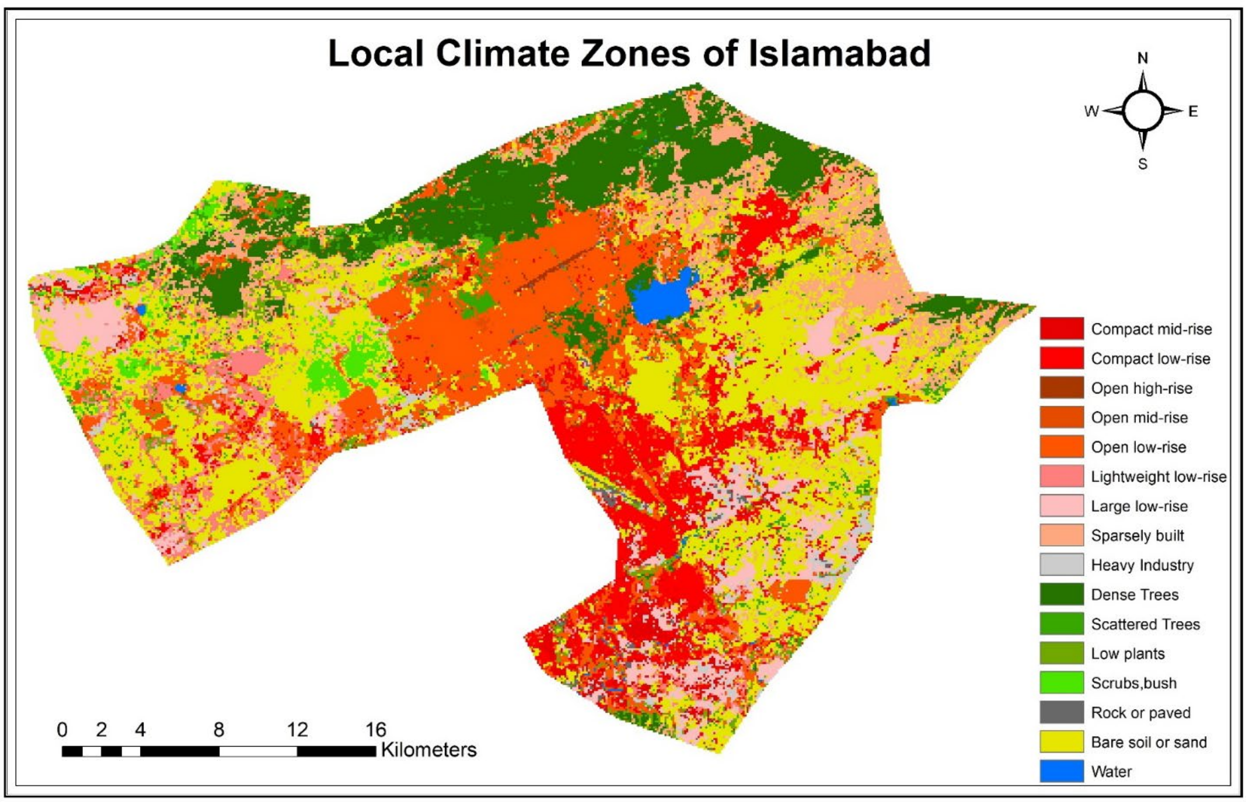

Figure 9 Local climate zones map of Islamabad 2019

Overall, it is evident from the outputs that the compact and open low-rise, i.e., LCZ 3 and LCZ 6, were the two most dominant classes in the study area. The buildings were more compact, and the open high-rise was present in the hub. A further increase in high-rise may damage the city's environment. The higher temperatures in the outskirts can be linked to the topographic differences and the presence of bare soil. The city centre belongs in the high-temperature risk hotspots, as the temperatures have already touched 46^{o}C. The National Park area needs to be preserved, and strict action is required against any development in Zone 3. The dense trees in the National Park can help reduce the overall temperatures in the city. Due to the rapid compact-low rise development, the temperatures have also increased towards the south direction. Any further increase could lead to severe thermal discomfort in the city, and therefore, for maintaining the city environment, all these factors should be considered for future developments and any urban extensions.

4.3 Implications for Islamabad

The current growth of Islamabad metropolitan is very much different from the vision of Doxiadis concept of dynapolis. The core and its centrality have decreased with the growing city. The city is bound by G.T. road, which limits its planned growth on the west side. In the North, Margalla hills are present, so the growth of the city is in the west and south directions. Continuous amendments and revisions of the master plan of Islamabad have been unable to keep up with initial visions of the city, i.e., following the concept of Doxiadis' dynametropolis. Due to the slow development of new planned sectors by the CDA, huge chunks of unplanned, haphazard, and leapfrog growth have started outside the city, showing an example where the core is planned and the exterior of the city is unplanned.

The results of the study show a rapid change in the land cover conditions of Islamabad city during 2013 and 2019. There was a strong and positive correlation between LST and NDBI and a negative correlation between LST and NDVI. In Zone 4, which is primarily designated for rural areas, forests and agro-farming have not been developed as planned. From the LCZ maps, it can be seen that most of the area is bare soil or land with mixed development patterns, which is affecting the thermal and environmental conditions of this zone.

LCZ can serve as the basis for the urban temperature studies of Islamabad; the rising temperature in the capital is a growing concern for climatologists and urban planners. Reducing green spaces is considered the main factor for increasing temperature. In Pakistan, the type of built-up and materials used for construction are usually ignored while devising urban expansion policies relating to climate change. The open spaces or the green areas need to be planned to contain the climate-friendly nature of the city, which can be measured via the coolest zones, i.e., LCZ G (water) and LCZ A (dense trees). Further high-rise construction should be done with proper planning and mitigation strategies, and the unplanned compact-low rise development needs to be adequately monitored (LCZ 6). The bare soil or sand areas, i.e., LCZ E, can be easily converted to LCZ B (scattered trees) and can significantly reduce heat and urban climate risks in the capital city.

The population in Islamabad has increased rapidly, leading to unplanned development in peripheral areas. Urban sprawl in Zones 2 and 4 is utilising the scarce land and affecting the city's climatic conditions. The LCZ map reveals that the most dominant classes in the area were LCZ 3 and LCZ 6, followed by LCZ F and LCZ A. The most rapid built-up was the LCZ 3 class in Zone 4 of Islamabad that was initially designed for agriculture use. Due to scarce land for future extensions, open low-rise might be unsuitable for providing compact development. Apart from Zone 4, the areas of Zone 3 (designated conservation zone) also need proper attention. As clearly seen from the LCZ maps of 2013 and 2019, some of the areas of Margalla hills national park has been consumed for development purposes. There has been a lot of compact/open low-rise (LCZ 3/LCZ 6) development in some areas; which is on the increase. It was less in 2013, and now it has increased; now, more of the land has been occupied for development purposes, which has also affected the dense tree cover. A dominant class of LCZ F (bare soil) was observed in the outskirts of the city, which can be transformed into greener areas to reduce thermal stresses in the built environment.

The use of LCZs has been increased worldwide for urban climate mapping, UHI assessment, and urban planning. LCZ classification has been used to get information about urban morphology and road networks to assist urban planners (He et al., 2018). Similarly, LCZ maps have been used to recommend vegetative land and water bodies to tackle climate change risk, plan future developments with increased spacing, and so on (Shih, 2017). The results derived from the LCZ maps can be used as an input to urban climate models and climatic spatial urban planning (Cai, Ren, Xu, Dai, & Wang, 2016).

It is recommended that future development plans should simultaneously focus on land use and local climate zoning for mitigating potential hotspots of climate risks in the city. The city administration could potentially evaluate the LCZs for working out sustainable and climate-resilient development solutions. In the current revision of the master plan, there is no reference to the LCZs or UHI effects. Without incorporating LCZs, the master plan could create urban risks in the future. LCZs can effectively help the authorities identify such potential high-risk areas and maintain thermal comfort in the city. This study can act as a foundation to understand the urban morphology of Islamabad and to assist the development of future urban plans and policies that could help mitigate the impacts of climate change and urbanisation on the local climate.

5. Conclusion

With the increasing threat of climate change-induced extreme events and rapid urban growth, climate and disaster risks will increase significantly. There is an urgent need for collaboration among urban planners and climatologists for relieving thermal stresses through climate-resilient development. The city of Islamabad is rapidly expanding, with a population above 1 million. The LULC analysis revealed that the built-up area increased significantly during a short period of 2013-2019 by a whopping 113% (vegetative area decreased by 33% during this period). The temperature in the city has also increased due to the expansion of built-up areas. The LCZ 3 (compact low-rise) and 6 (open low-rise) were the most dominant classes. Irregular and unplanned development has transformed these areas into hotspots, and attention is needed for future development. It has been suggested to incorporate LCZs in future master plan revisions and planning policies.

Even with certain limitations, such as lack of availability of detailed urban planning data and digital master plan maps, the study was quite successful at determining the rate of LULC change and LCZs to understand the spatiotemporal characteristics of urbanisation. The output of the LCZ model, however, could be improved using detailed urban planning data/maps, advanced/high-resolution and aerial satellite imageries, and ground-level data. More advanced techniques and physical parameters of geometric and surface cover properties can also be incorporated to properly reflect ground realities. Moreover, factors such as air temperature, wind conditions, and morphological parameters can be included to better understand the effect of different LCZ types. The methods proposed in this study can act as the cornerstone for further research on urbanisation and LCZ studies in other developing countries.

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