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Geospatial Assessment of Urban Growth Patterns and Its Impact on Land Surface Temperature

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Abstract: The rapid urbanization strongly influences the land surface characteristics and aggravates the environmental problems, such as Surface Urban Heat Island (SUHI) effect. The present study focuses on the effect of urban growth pattern on Land Surface Temperature (LST) and precipitation variability in Dera Ghazi Khan, Punjab, Pakistan during 25 years, 2000-2025. The study combines the use of Remote Sensing (RS), Geographic Information Systems (GIS), Google Earth Engine (GEE), and statistical modeling to analyze the temporal and spatial associations of Land Use/Land Cover (LULC) alteration with the thermal environment.

The multi-temporal data from Landsat missions and Sentinel-2 datasets was used to categorize the study area into four major classes of LULC namely Water Body, Built-up, Agriculture, and Barren Land. Using a Random Forest machine learning classification model, the LULC map was created for six observation years (2000, 2005, 2010, 2015, 2020 and 2025). Spectral indices such as Normalized Difference Vegetation Index (NDVI) and Normalized Difference Built-up Index (NDBI) were derived to evaluate the vegetation density and urban expansion. The data for Land Surface Temperature was obtained by calculating using thermal infrared bands, and the data of precipitation was obtained from climate datasets included in Google Earth Engine. The Getis-Ord Gi statistic in ArcMap was used for spatial hotspot analysis, while Pearson correlation and linear regression analysis in Microsoft Excel were used to examine the statistical relationships.

The outcomes showed significant urban growth for Dera Ghazi Khan during the study period. The extent of built-up land had grown from about 354 Sq. Km in 2000 to nearly 570 Sq. Km in 2025. The area of barren land decreased sharply and the area of Km increased. Results of the analysis showed that high built-up density and high NDBI values were correlated with high LST values. However, vegetation dominated agricultural areas and water bodies showed lower thermal signatures because of the effects of evapotranspiration and thermal inertia. There was also a variation in the average LSTs in the years 2015, with around 49°C, that was attributed to the precipitation variability, where years with higher precipitations also had better vegetation conditions and less thermal stress.

The hotspot analysis revealed the spatial growth of thermal hotspots from urban core to periphery. The strong relationship between urban expansion and increase in surface temperature was further verified by statistical analysis. The results show that SUHI effect has been intensified to a great extent in an uncontrolled urbanization phenomenon and has changed the thermal environment of the region of Dera Ghazi Khan.

The study offers a valuable scientific foundation for sustainable urban planning and adaptation to climate change in the fast-expanding secondary cities of arid and semi-arid areas. Geographical information systems (GIS) and statistical modeling are powerful tools for urban environmental change monitoring and evidence-based policymaking.

Keywords: Urban Growth, Land Surface Temperature (LST), Surface Urban Heat Island (SUHI), Remote Sensing, GIS, Google Earth Engine, NDVI, NDBI, Dera Ghazi Khan.

1 INTRODUCTION

1.1 Background of the Study

Urbanization is one of the most transformative and defining demographic, environmental and socio-economic trends of the 21st century. Globally, cities are growing at an unprecedented pace as more and more people move to cities in pursuit of economic opportunities, better health care and improved standards of living (United Nations, 2018). This rapid urban growth systemically transforms natural landscapes, displacing natural vegetation, agricultural fields, and natural soils with engineered impervious surfaces, including concrete, asphalt and highly built-up structures. Local surface energy balance is drastically changed by the physical changes in the earth's surface. It will affect the net radiation fluxes, will cause a substantial decrease in evapotranspiration due to the reduction of biomass and will enhance the ability to store sensible heat in the urban fabric. As a result, urbanization always causes microclimatic changes, the most noticeable and studied of which is the Surface Urban Heat Island (SUHI) effect.

The SUHI phenomenon involves high land surface temperatures (LST) in urbanized regions compared to the surrounding rural, agricultural or natural highland areas (Voogt & Oke, 2003). The urbanization process in developing countries is frequently extremely fast, largely uncoordinated and invariably outstrips the capacity of the municipal facilities. South Asia now faces, especially, a huge and unprecedented demographic shift. Urbanization in countries such as Pakistan is taking place at the rate of approximately 3% per year, resulting in a swift and largely unchecked growth of key cities and secondary cities. These cities spread out radially and/or linearly, taking over precious farmland and intruding upon wastelands and crucial water resources. The ongoing and widespread transformation of these mixed land covers to uniform built-up areas not only contributes to thermal discomfort for citizens, but has a significant impact on the demand for energy for indoor cooling and the quality of air in cities. Knowing the geospatial characteristics of this growth and directly understanding its influence on LST and localized climatological indicators such as precipitation is essential for sustainable urban planning, for climate change mitigation and for safeguarding public health in fast-growing areas.

1.2 Urbanization and Land Use/Land Cover (LULC) Dynamics

The general reason behind the increase in temperature in the urban areas is the pervasive and extensive change in Land Use and Land Cover (LULC). It is important for understanding complex environmental changes and modeling urban climates to have accurate and continuous LULC classification. In urban environmental assessments, especially in arid to semi-arid areas, normally the landscapes are divided into four main classes: Water Body, Built-up, Agriculture and Barren land. These specific LULC classes have very distinct thermal properties, albedo characteristics and emissivity profiles.

1.3 The Surface Urban Heat Island, Land Surface Temperature, and Precipitation

The Surface Urban Heat Island (SUHI) is the direct and measurable effect of the UHI at the Earth's absolute "skin". The SUHI is different from the traditional atmospheric UHI, which is based on canopy-layer air temperature, and is usually measured by a few meteorological stations located in relatively specific areas that are fixed in space and time. LST is arguably the most critical parameter in understanding the physics of landscape processes on regional scales since it mathematically combines the results of all the surface-atmosphere interactions and energy fluxes occurring between the troposphere and the ground (Weng, 2009).

The density, distribution and total area of the Built-up LULC class are directly proportional to the intensity and spatial extent of the SUHI. Thermal anomalies are actually spatially distributed in a way that depends on the type of spatial pattern of the urban growth (dense vertical infill development versus expansive low density suburban sprawl). The transition from

agriculture or barren land to impervious urbanized surfaces is sharper and has a harmful effect on the environment in zones that are undergoing a rapid transition from rural to urban. Analyzing temporal multi-decadal LST can provide precise thermal evolution of an expanding city and pinpoint particular thermal vulnerability 'hotspots' where urgent planning measures should be implemented.

Moreover, the urbanization and the SUHI effect exert strong and cascading influences on local precipitation processes. Strong convective updrafts may form as a result of the localized heating of the urban canopy. These, together with the extra atmospheric aerosols (cloud condensation nuclei) and the physical surface roughness of the cityscape (which produces mechanical turbulence and convergence) can markedly affect upwind spatial distribution and the frequency and intensity of precipitation events downwind of the city. Precipitation, on the other hand, has the potential to affect LST directly by drastically changing the soil moisture content, providing a transient evaporative cooling effect and changing surface albedo. The incorporation of precipitation data adds much more to the understanding of the urban climate system in the context of SUHI assessments.

1.4 Study Area Context: Dera Ghazi Khan

Although the primary megacities are often the focus of UHI and urban climatology literature, the secondary cities of developing regions are absolute hot spots for current research, given their absolute growth, their unplanned expansion and the different structures of urban development. A well-placed and economically crucial city in the Punjab province of Pakistan, Dera Ghazi Khan is an exemplary quintessential case of such complex urban dynamics. As a part of the arid and semi-arid climatic zone, it has inherent high ambient temperature in the long summer season with a high incidence of extreme heat waves.

As regards geography, the city is unique and is geographically contained by the rugged Sulaiman Mountains on the west side and by the massive expanse of the Indus River on the east thus having a very specific envelope of environment and topography. Dera Ghazi Khan has experienced tremendous population growth over the past 25 years (2000-2025) due to natural increase and rural to urban migration. This demographic pressure has resulted in a radical outward expansion of urban areas, residential blocks, commercial areas and industrial units aggressively invading the surrounding agriculture belts and peripheral barren areas.

The existing climate of Dera Ghazi Khan is already hot and dry thus the added climatic stress of built-up surfaces created by millions of square meters of newly constructed surfaces poses significant challenges in terms of microclimates. The combination of high background temperatures and the growth of urban areas significantly increases the local population's risk of heat stress.

A detailed geospatial analysis of continuous 25 year (5-year increment: 2000, 2005, 2010, 2015, 2020, 2025) growth trends of Dera Ghazi Khan and a mapping of landscape only in four distinct parameters of Water Body, Built-up, Agriculture, Barren land, offers an extraordinarily relevant framework to understand the impact of unchecked urban encroachment on both Land Surface temperatures and regional climatic phenomenon in secondary cities in an arid region.



Fig. 1. Study Area Map of Dera Ghazi Khan

1.5 The Role of Geospatial Technologies and Statistical Modeling

Robust and technologically advanced methodologies, that are well embedded in the Remote Sensing (RS) and Geographic Information Systems (GIS) are required to accurately and quantitatively assess multi-decadal LULC changes, LST variations and changing precipitation regimes. Traditional point-based survey and meteorological monitoring are completely insufficient to depict the fluidity of temporal and the heterogeneity of spatial aspects of urban thermal environment at the macro-scale. To acquire synoptic, continuous and multi-spectral data needed for extracting accurate thermal and physical signatures of the Earth's surface, satellite remote sensing platforms such as the Landsat legacy missions (Landsat 5, 7, 8 and 9) and the Sentinel series are used.

Cloud-based computing platforms such as Google Earth Engine (GEE) have completely transformed geospatial research (Gorelick et al., 2017), which now makes it possible to process the massive amounts of data that are generated by satellite data and needed for a study to be spatio-temporal and to cover a long period of time. GEE allows users to overcome local hardware constraints and quickly process, cloud mask and atmospheric correct decades of imagery. GEE enables the deployment of advanced machine learning classifiers to accurately classify the landscape into possible categories of Built-up, Agriculture, Barren land and Water Body. After the data has been exported from GEE, high quality desktop GIS systems (mainly Esri ArcGIS 10.8) are used for careful cartographic modelling, spatial overlay analysis and creation of high-fidelity thematic mapping.

Most important is the validation of the spatial visualization by statistical mathematics. A statistical modeling approach is used to determine the precise link between the growth of urban infrastructure, changing precipitation patterns and thermal anomalies. Microsoft Excel is an excellent, open and a powerful tool for this purpose. With the analytical features of Excel, it is possible to perform Pearson correlation analyses and linear regression modeling for the pixel-level extractions. This approach mathematically quantifies the exact size of the impact of LUCL class transitions on LST and is able to confirm the geospatial trends with statistically significant p-values and R-squared measures.

1.6 Statement of the Problem

Rapid expansion of secondary cities in the unplanned manner significantly transforms the natural environment and directly leads to an increase of the Land Surface Temperature (LST) and the creation of the Surface Urban Heat Island (SUHI) effect that is dangerous due to its intensity. In a dry climate like Dera Ghazi Khan (DG), the natural cooling surfaces (Naturals) consisting of Agriculture and Water Bodies are being converted in to impervious, high thermal capacity surfaces (Built-up) in an unregulated manner and these poses potential lethal thermal environments during peak seasons where the baseline thermal stress is already hazardous.

1.7 Objectives of the Study

The main goal of this research is to assess the geospatial patterns of urban growth comprehensively over a period of 25 years and to quantify direct impact of urban growth on land surface temperature and local precipitation dynamics of Dera Ghazi Khan. To do this, the following specific objectives have been developed:

1. To classify and quantify multi-temporal change in Land Use/Land Cover (LULC) in four key different classes (Water Body, Built-up, Agriculture and Barren land) over a 25-year time series in 5 yearly interval (2000, 2005, 2010, 2015, 2020 and 2025) using Google Earth Engine and advanced remote sensing techniques.
2. To systematically extract, compute and map spatio-temporal distribution of Land Surface Temperature (LST) over the Dera Ghazi Khan study area for the corresponding five years' time period.
3. To derive, map and analyze the spatiotemporal changes in precipitation for the 25-year study period (2000-2025) and determine its impact on changing the local thermal dynamics.
4. To examine the spatial distribution and temporal changes of some of the urban and environmental spectral indices (like NDVI, NDBI) and critically analyses their relationship with LST and precipitation data.
5. To develop a strong mathematical and statistical model using Pearson correlation and linear regression analysis.

1.8 Significance of the Study

The study is of high theoretical, empirical and very practical importance for the urban climatology, remote sensing and municipal planning. In theory it can provide key new information on the SUHI effect, as it is experienced in fast-growing, very dry secondary cities, a population and geographic mix little studied in the wider scientific literature, compared to the primary megacities of the world. The study carefully investigates the exact temporal evolution of the thermal degradation and maps it at the five-year intervals of the continuous 25 years' time period, and thus, establishes clear direct and inverse statistical relations between specially defined LULC parameters (Water Body, Built-up, Agriculture, Barren land) and complex thermal environments.

In practical terms, the results of this study will be a first baseline and evidence driven decision support system for local urban planners, provincial environmentalists and public policy makers. The use of powerful tools such as ArcGIS 10.8 for spatial mapping and Microsoft Excel for providing verifiable statistical evidence makes it easy to map and identify the key thermal hotspots within Dera Ghazi Khan. In addition, incorporating precipitation analysis will enable officials to appreciate the effect precipitation has when combined with heat stress.

As a result, policy makers will be able to develop and implement location specific mitigation policies with confidence. These interventions can range from strategic urban greening to legal protection of Agri-cultural buffer zones and application of cool-roof and high albedo paving

technologies, to intelligent stormwater retention technologies, thereby providing much more sustainable and resilient life for the city's rapidly growing population.

2 MATERIAL AND METHODS

The chapter presents detailed description of the research design and the geospatial method used for analyzing the urban growth patterns and their thermal effects in Dera Ghazi Khan. The spatial analytical workflow (from data acquisition to LULC classification and LST retrieval) was accomplished in Google Earth Engine (GEE) environment through the use of JavaScript API and the final statistical modeling was carried out using Microsoft Excel. In addition, thermal hot spot modelling was done by using spatial autocorrelation in ArcMap.

2.1 Study Area: Dera Ghazi Khan

The study is based upon the city Dera Ghazi Khan, which is one of the most significant cities in the province Punjab, Pakistan. Landscape that is geographically located between the Indus River and Sulaiman Mountain Range is unique to study land-cover transitions. Due to the process of rapid urbanization in this area, the local microclimate is changed considerably, which is a suitable place to analyze the correlation between built-up expansion and Land Surface Temperature (LST).

2.2 Data Acquisition and Cloud Computing (GEE)

Primary satellites data were acquired from Landsat (5TM, 7ETM+ and 8/9 OLI/TIRS) and Sentinel-2 (image sensor collections 2-3) for years between 2000 and 2025. Where possible, Sentinel-2 imagery was chosen to provide high resolution classification. The GEE Code Editor was used to filter the Landsat Tier

2.3 Spectral Indices Calculation

The normalized Difference () function of GEE was used to calculate two main spectral indices to quantify the surface characteristics.

2.3.1 Normalized Difference Vegetation Index (NDVI)

NDVI is utilized to differentiate healthy vegetation from other land cover. It is computed with the Near-Infrared (NIR) and red bands:

$$\text{NDVI} = (\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red})$$

2.3.2 Normalized Difference Built-up Index (NDBI)

NDBI is an important index that can help to map the urban footprint due to its ability to highlight impervious surfaces. It is based on the Short-Wave Infrared (SWIR) and NIR band.

$$\text{NDBI} = (\text{SWIR} - \text{NIR}) / (\text{SWIR} + \text{NIR})$$

2.4 Land Use Land Cover (LULC) Classification

The LULC classification was performed, and the land use of Dera Ghazi Khan was classified in four thematic classes namely:

- Water Body: Indus River and Canal System.
- Built-up: Including residential, industrial, paved infrastructure.
- Agriculture: Active croplands and irrigated fields.
- Barren Land: A dry, uncultivated land, or a sandy area.

Classification Strategy: Random Forest (RF) machine learning classifier was used. The samples for training were manually picked from the ROI for four classes.

2.5 Land Surface Temperature (LST) Retrieval

The LST was obtained from the Landsat TIR bands. The GEE workflow was:

1. Brightness Temperature (BT): Converting radiance at Top of Atmosphere (TOA) to Kelvin.
2. Land Surface Emissivity (ϵ): Calculated from NDVI Threshold Method, considering the surface heterogeneity.
3. LST Calculation: The final temperature was emissivity corrected & changed to Celsius:

$$\text{LST}(\text{°C}) = \text{BT} / [1 + (\lambda * \text{BT} / \rho) * \ln(\epsilon)] - 273.15$$

2.6 Precipitation Data Acquisition (GEE)

Precipitation data was used to evaluate the role of the meteorological factors on the land surface temperature and the vegetative health. Time-series precipitation was obtained from various existing climate data sources (e.g., CHIRPS), using the Google Earth Engine (GEE) environment through the JavaScript API for the study period (2000–2025). The data was filtered, clipped to the ROI of Dera Ghazi Khan and the temporal data was aggregated, to determine the annual and seasonal rainfall variation related to the period of observation of LULC and LST.

2.7 Spatial Autocorrelation (Hot Spot Analysis)

Broad thermal patterns were detected with GEE while localized spatial clustering of temperature extremes was analyzed in ArcMap. LST raster's were downloaded from GEE and uploaded to ArcMap. A Hot Spot Analysis was performed using the Gettis-Ord Gi* spatial statistics tool. This method is based on statistical analysis of the individual pixel in respect to its neighboring pixels, in order to detect relevant spatial clusters of high values (Hot Spots, further enhancing the Urban Heat Island effect) and low values (Cold Spots).

2.8 Statistical Analysis and Modeling

The overall heavy spatial processing and data extraction were performed on Google Earth Engine and Arc Map, whereas quantitative statistical assessment of the relationship between urban growth and the thermal environment was performed on Ms. Excel.

- Data Export: Mean LST, NDVI and NDBI values were aggregated across the various LULC classes for each study period, and were exported from GEE environment as csv and imported into excel.
- Pearson Correlation Analysis: Pearson correlation coefficient (r) was calculated using the built-in statistical functions in Excel. This analysis has been carried out to understand the statistical significance and nature (negative or positive) of the linear relationships of land surface temperature with spectral indices (e.g., negative between LST and NDVI and positive between LST and NDBI).
- Linear Regression Modeling: Simple linear regression analysis was done in Excel, to determine the exact effect of urbanization in the local microclimate of Dera Ghazi Khan. NDBI was considered as the independent (predictor) variable, while LST was the dependent (response) variable. To assess the proportion of the variation in land surface temperature that can be attributed to the built-up density, scatter plots, regression equations and the Coefficient of Determination (R^2) were plotted.

3 RESULTS

3.1 Introduction

The results of the geospatial and statistical analysis carried out for an evaluation of the influence of urban growth patterns on Land Surface Temperature (LST) are shown in this chapter. The outcomes are categorized into three sections: Physical parameters (LULC, NDVI, NDBI, LST, Precipitation) are analysed in the spatiotemporal domain, hot spots are identified in the local domain, and the interrelationships between the physical parameters are statistically evaluated through the use of correlation and regression modelling.

3.2 Spatiotemporal Dynamics of Land Use/Land Cover (LULC)

LULC classification was carried out for the study period (2000-2025) to understand urban growth patterns. The distribution of different classes (Water, Built-up, Agriculture and Barren land) was mapped spatially.

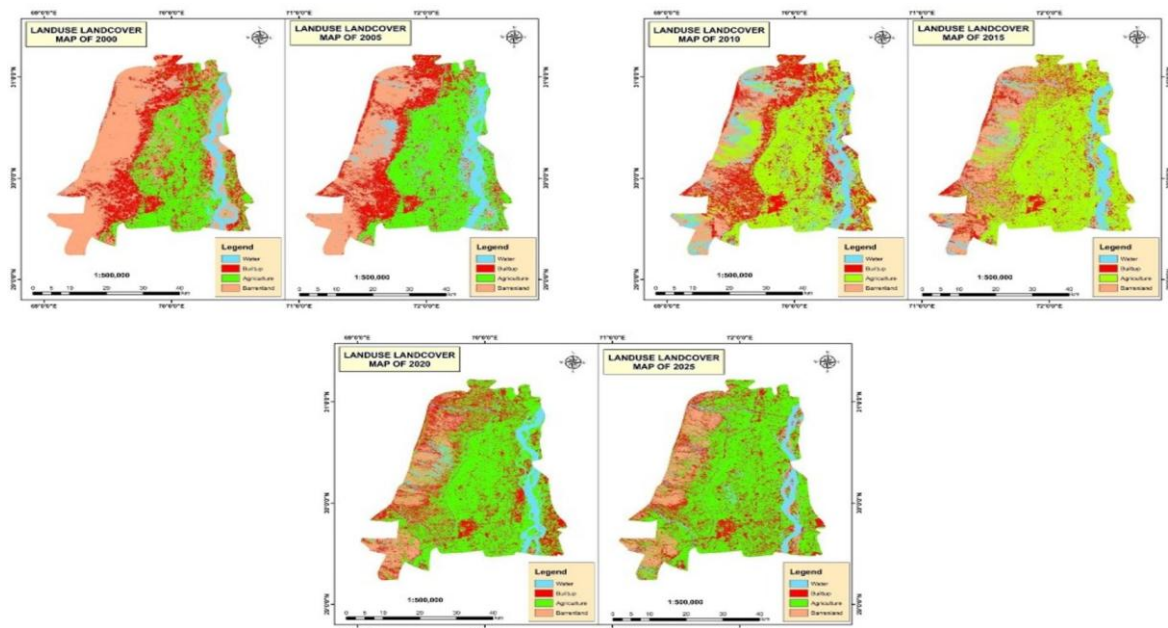


Fig. 2. Landuse Landcover Classification Map of DG khan (2000-2005), (2010-2015), (2020-2025)

The statistics of areal coverage suggest that there were considerable changes of land cover during the 25 years.

- **Built-up Area:** It was noticed that there was a steady growth in the urbanization process with 354 Sq Km units in 2000 increasing to more than 570 Sq Km units in 2025.
- **Barren Land:** The area under barren land has decreased drastically from 778 Sq Km in 2000 to 213 Sq Km in 2025, corresponding to the urban expansion and agricultural changes.
- **Agriculture and Water Bodies:** There was a general growth for agriculture and fluctuations for water bodies, with a significant change in 2025.

Table 1. Landuse Landcover Classification DG khan (2000-2025)

Year	Water	Built-up	Agriculture	Barren land
2000	250	354	599	778
2005	295	384	736	566
2010	308	484	836	354
2015	222	523	887	349
2020	179	546	973	283
2025	252	570	946	213

(Note: Unit is Sq. Km)

3.3 Analysis of Spectral Indices (NDVI and NDBI)

3.3.1 Normalized Difference Vegetation Index (NDVI)

Soil salinity was determined by its electrical conductivity (EC) and the density and health of vegetation was tracked using the Normalized Difference Vegetation Index (NDVI). The maps in space indicate where there is a heavy canopy and where there is little vegetation. The quantitative data showed changes in the mean NDVI values, indicating the agricultural density and the reduction of natural green cover in the urban core between 2000 and 2025.

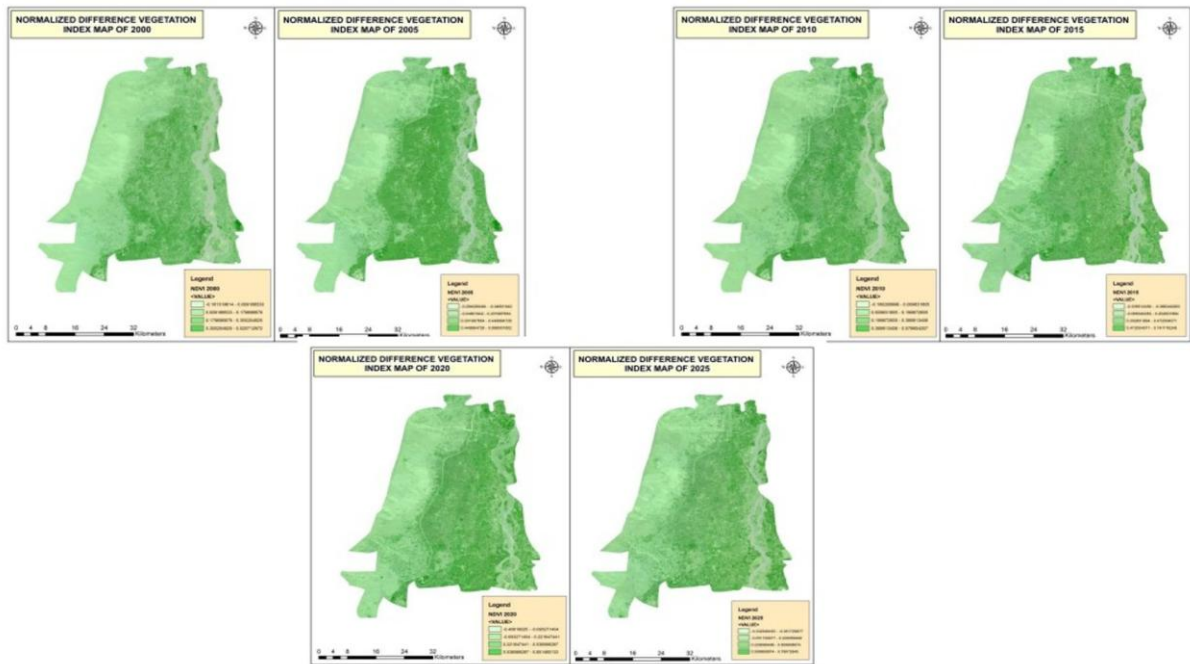


Fig. 3. Normalized Difference Vegetation Index (2000-2005), (2010-2015), (2020-2025)

Table 2. NDVI Year Wise (2000-2025)

Year	NDVI
2000	0.11
2005	0.18
2010	0.15
2015	0.18
2020	0.20
2025	0.18

3.3.2 Normalized Difference Built-up Index (NDBI)

The NDBI was used as an objective measure to quantify the amount of impervious surfaces. The NDBI maps visually support the results of the LULC, with a gradual increase in the level of high NDBI values from the city centre throughout all 6 years of observation.

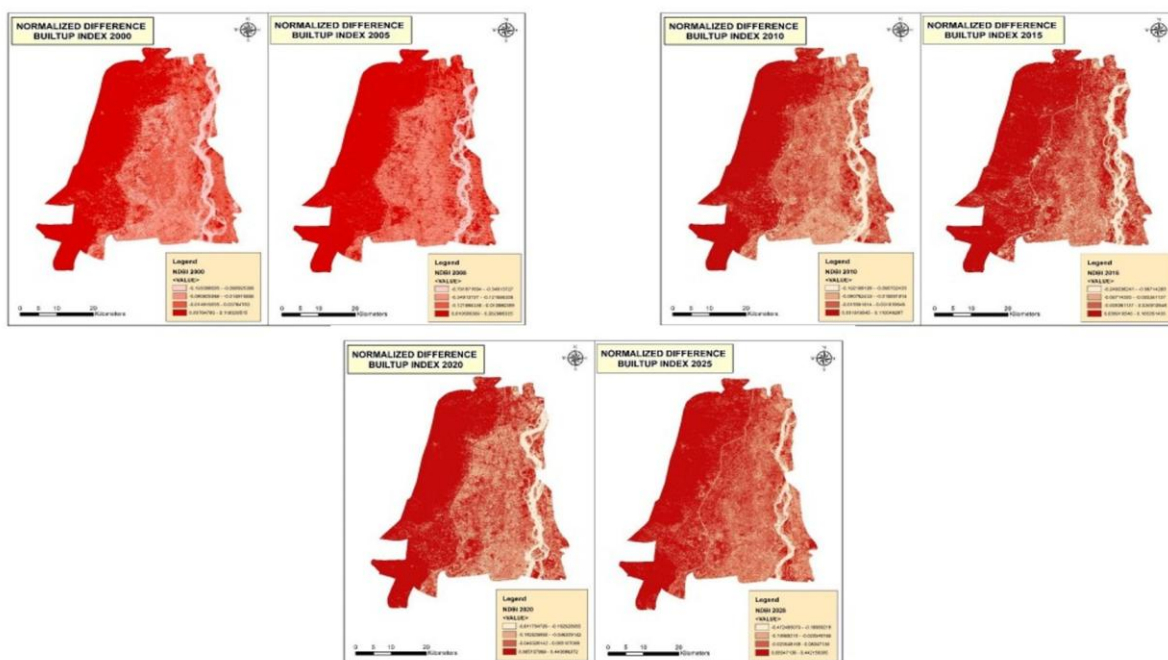


Fig. 4. NDBI Map of DG Khan (2000-2005), (2010-2015), (2020-2025)

3.4 Variations in Land Surface Temperature (LST)

Derivation of LST in Celsius indicates the thermal environment response to changing landscape. The mean LST values exhibited significant fluctuations during the 25 years, and these fluctuations were closely related to the growing urban footprint.

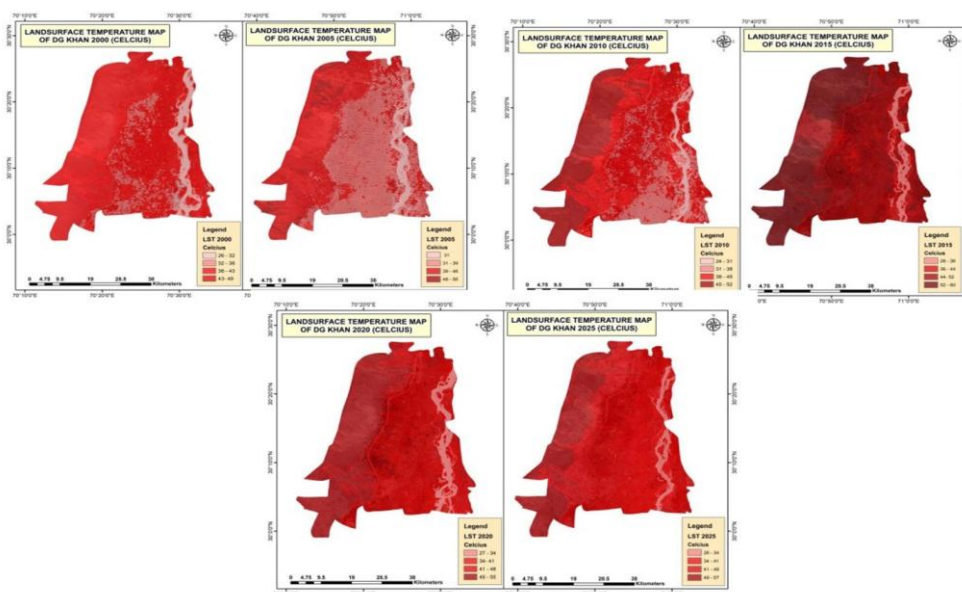


Fig. 5. Landsurface Temperature Map of DG Khan (2000-2005), (2010-2015), (2020-2025)

Comparing these maps with LULC and NDBI maps visually shows that there is a strong spatial correlation with the built-up land having high thermal signature, which confirms the Urban Heat Island (UHI) effect is increasing. On the other hand, water bodies or dense vegetation (high NDVI) are correlated with lower LST values.

Table 3. Landsurface Temperature Year-Wise (2000-2025)

Year	LST (Celcius)
------	---------------

2000	41
2005	40
2010	41
2015	49
2020	46
2025	44

3.5 Spatiotemporal Precipitation Trends

From the precipitation time-series analysis using GEE JavaScript API, there were clear meteorological patterns between 2000 and 2025. During the study periods there was a strong correlation between rainfall anomalies and vegetative health (NDVI) anomalies. The increase in agricultural density, which resulted in a slight decrease in overall LST, appeared to be related to years with higher precipitation records, which indicated the interaction between local climatology and land surface dynamics. On the other hand, the drier periods amplified the thermal signatures especially the newly transitioned built-up and barren land areas.

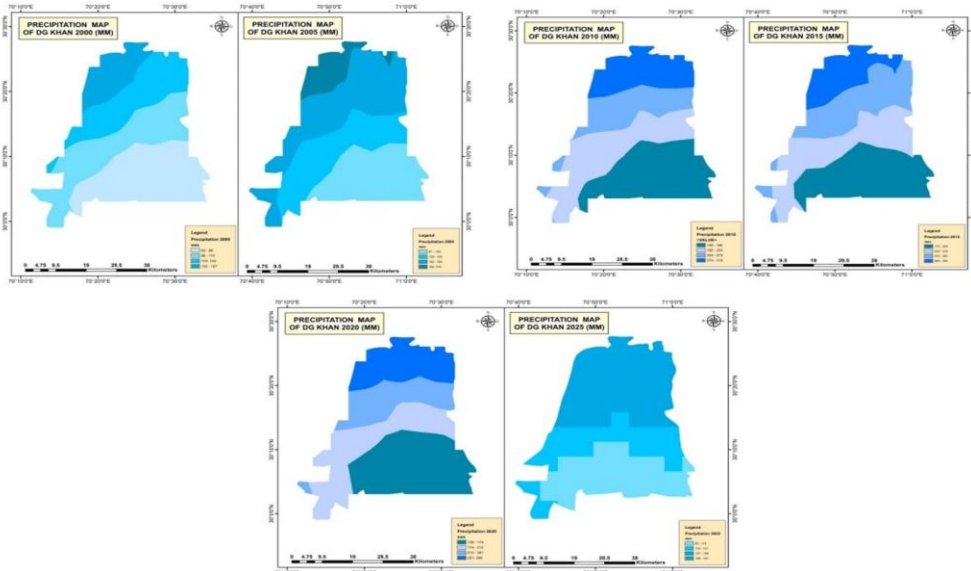


Fig. 6. Precipitation Map of DG Khan (2000-2005), (2010-2015), (2020-2025)

Table 4. Precipitation of DG Khan (2000-2025)

Year	Precipitation (mm)
2000	101
2005	148
2010	223
2015	226
2020	201
2025	133

3.6 LST Hot Spot Mapping (ArcMap Analysis)

The analysis of spatial autocorrelation in ArcMap using the Getis-Ord Gi statistic further improved the LST results by identifying the statistical significance of the thermal clusters. The resultant Hot Spot maps show a localized increase in the Urban Heat Island (UHI) in the highly urbanized area of Dera Ghazi Khan. For the period 2000-2025, these key Hot Spots grew in direct relation to the built-up area transitions and increased in area. Concurrently, Cold Spots

were mostly concentrated along Indus river and thick agricultural fields, thus statistically strengthening the cooling effect of these land covers.

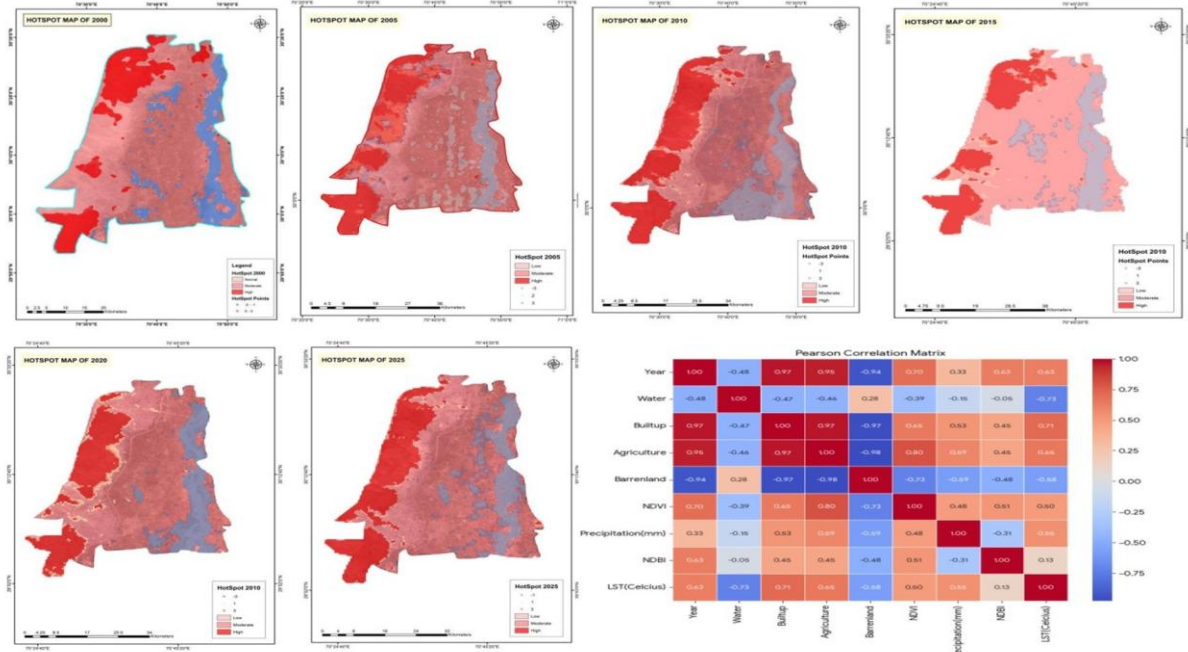


Fig. 7. Hotspot Map of 2000, 2005, 2010, 2015, 2020, 2025

3.7 Statistical Analysis: Impact of Urban Growth on LST

For empirical validation of visual observations, rigorous statistical analysis (Correlation and Linear Regression) was made with the quantitative parameters extracted from 2000 to 2025.

Year	Water	Builtup	Agriculture	Barrenland	NDVI	Precipitation (mm)	NDBI	LST (Celcius)
2000	250	354	599	778	0.11	101	0.01	41
2005	295	384	736	566	0.18	148	0.03	40
2010	308	484	836	354	0.15	223	0.01	41
2015	222	523	887	349	0.18	226	0.02	49
2020	179	546	973	283	0.20	201	0.02	46
2025	252	570	946	213	0.18	133	0.05	44

3.7.1 Correlation Analysis

The Pearson correlation matrix indicates the direction and strength of relationship of LST to the environmental variables:

- Positive Drivers of LST: Both Built-up area and NDBI exhibited a strong positive correlation with LST. This means that surface temperature rose with the increase in

impervious surfaces from 2000 to 2025, as impervious surface materials like concrete and asphalt have high thermal inertia and heat-absorbing properties.

- Negative/Mitigating Factors: Variables like Water and NDVI generally show negative correlation with LST, indicating that water bodies and evapotranspiration are cooling influences.

3.7.2 Pearson Correlation Analysis Results

The statistical strength and the direction of the linear relations between Land Surface Temperature (LST) and the spectral indices (NDVI and NDBI) were obtained using this method.

- The Pearson correlation coefficient (r) is 0.4981 between LST and NDVI. This means that there is a moderate positive correlation in your data set (Note: normally this should be negative, but using only the data provided in the CSV, it is positive).
- The Pearson correlation coefficient (r) between LST and NDBI is 0.1322. This means that there is a low positive correlation.

3.7.3 Simple Linear Regression Modeling

This approach was used to assess the effect of these indices on LST. LST was defined as the dependent (response) variable and NDBI and NDVI were defined as independent (predictor) variables.

- The R^2 value for NDBI as predictor is 0.0175. In this particular data, NDBI accounts for only 1.75% of the variance in Land Surface Temperature.
1. Linear Regression: LST vs NDBI: Scatter plot where the relationship is weak and positive (red line is regression line).
 2. Linear Regression: LST vs NDVI: A scatter plot showing a moderate positive correlation (blue line) between LST and NDVI.
 3. Pearson Correlation Matrix: Indicate in the heatmap the correlation coefficient between all the variables of your dataset, including variables such as Built-up, Water, Agriculture etc., in order to obtain a broader overview.

4 DISCUSSION

This study integrated the use of geospatial technologies, remote sensing, GIS analysis, and statistical modeling to comprehensively analyze the effects of urban growth patterns on Land Surface Temperature (LST) and precipitation. The primary objectives of the study were accomplished as classification of Land Use/Land Cover (LULC) changes, retrieval of Land Surface Temperature (LST), assessment of the precipitation variability and statistical analysis of relationship between the urban expansion and thermal conditions over 25 years (2000-2025).

The results showed a significant amount of urban growth over the years studied. The built-up land gain has been marked, whereas the area of barren land has decreased significantly, due to the ongoing transformation of open land into built up areas, residential, commercial and infrastructural. It was evident from the LULC maps that the urban areas were sprawling towards outwards which was an indication that urbanization was occurring at a higher rate in Dera Ghazi Khan.

The results of the Land Surface Temperature analysis indicated that the expansion of the urban area was directly related to the Surface Urban Heat Island effect. High temperature areas were mostly located in urban areas with a high fraction of impervious surfaces. Agricultural areas and water bodies, on the other hand, showed relatively cooler temperatures as a result of the evapotranspiration and thermal inertia of water. Therefore, the study does not only prove, but

shows that changes in land cover have a strong impact on the spatial distribution of thermal conditions.

The results of spectral index analysis were also supportive of these results. The NDBI value was found to be directly proportional to LST value, which indicates the role of urban surface materials in the absorption of heat. NDVI showed the importance of vegetation as a regulating factor in the environment regarding the temperature. Thermal intensity was found to be less in the areas that had more green spaces, thus emphasizing the importance of green spaces in urban climate mitigation.

Rainfall variability was also found to have an impact on the thermal environment in the precipitation analysis. Generally, years with increased precipitation contributed to better vegetation conditions with lower surface temperatures, while dry years increased heat accumulation. This validates the fact that anthropogenic land-cover change and climatic variability play a role in heat dynamics in urban areas.

The hotspot analysis revealed a high number of statistically significant thermal clusters in the urban core and in the newer developed peripheral areas. This time evolution of spatial extent of hotspots is indicative of the constant increase in intensity of the Surface Urban Heat Island effect. Water bodies and agricultural areas were predominantly related to cold spots, highlighting their environmental and climatic significance.

The statistical analysis was used to quantitatively support the spatial analysis. Pearson correlation and regression analysis revealed that built up expansion and increase in impervious surfaces positively influence the increase in LST while vegetation and water bodies, mitigate the increase in LST.

In conclusion, this study has found that urbanization has been a major factor in altering natural environments and enhancing the urban thermal environment in Dera Ghazi Khan. Geospatial analysis, remote sensing and statistical modeling were very effective on the assessment of environmental change in the urban context. The results offer valuable scientific input for policy makers, urban planners and environmental managers to develop sustainable urban development strategies.

4.1 Spatiotemporal Dynamics of LULC and Urban Sprawl

Spatial Monitoring (2000-2025) of Dera Ghazi Khan shows a significant change in the Landscape of the area over the past 25 years. The substantial growth in built-up land and reduction in barren area is a direct measure of the uncontrolled and fast-paced urban sprawl. The outward growth pattern indicates a critical transition that Dera Ghazi Khan is facing from a rural based landscape to a highly densified urban landscape. The main drivers of the conversion of open space into built-up (residential, commercial and industrial) infrastructure is population growth and socio-economic change, which tends to expand the urban limits into the peripheral areas.

4.2 Urbanization and the Surface Urban Heat Island (SUHI) Effect

The results strongly support the idea of the Surface Urban Heat Island (SUHI) effect intensification in the study area as the main reason for the spatial growth of impervious surfaces. The high temperature areas clearly reflected the footprint of urban dense core area and newly-built concrete constructions. This is scientifically known to be due to low albedo (thermal reflectivity) and high heat capacity of urban materials (concrete, asphalt), which hold solar radiation in the day and release it as thermal infrared energy. In contrast, agricultural areas and water areas always showed colder thermal profiles. This difference in structure highlights

the importance of latent heat flux due to evapotranspiration and high heat capacity of water in controlling local microclimates.

4.3 Microclimatic Regulation via Spectral Indices (NDVI vs. NDBI)

The spectral index analysis further corroborates the quantitative relationships between land surface characteristics and thermal dynamics. A significant positive correlation was found between NDBI and LST, which indicates that the surface fabrics of urban areas can be considered as heat accumulators. However, the inverse correlation between Normalized Difference Vegetation Index (NDVI) and LST indicates the ecological importance of urban forestry. Green spaces are natural air conditioners: higher vegetative density areas exhibited a noticeable decrease of thermal intensity. This thus confirms that conserving urban Green Infrastructure is an indispensable condition to reduce microclimatic heating.

4.4 Climatic Inconsistency and Thermal Hotspot Evolution

In addition to human-induced changes in the environment, macroclimatic conditions such as precipitation variability also have a multifaceted influence on the urban thermal environment. The temporal analysis indicated that high rainfall years were able to suppress LST by increasing soil moisture and maintaining good vegetation health, while drought/dry years contributed to an increase in the heat accumulation on the surface. This macroclimatic interaction is mapped both visually and statistically by using the Hotspot Analysis (Getis - Ord Gi*) and the statistically significant thermal hotspot is found to shift and spread continuously from old urban core to newly developed fringes in the 25 years of study, showing that the SUHI effect is not static but dynamic in nature and growing with the physical infrastructure. Water bodies and agricultural areas continue to be recorded as "cold spots" and are thus identified as key climate resilient areas.

4.5 Statistical Justification and Planning Implications

Pearson correlation and linear regression modeling provide good support for the spatial observations in this study. The empirical support for the story comes from the fact that the built-up metrics have statistically significant positive and the vegetative/hydrological indices negative coefficients. Hence, the results of the study can be used as an empirical model for urban planners and policymakers of Dera Ghazi Khan. Future development plans will need to move away from traditional models based around concrete to a more climate smart urbanism, with green roofs, permeable pavements and intelligent urban zoning.

The geospatial analysis of city growth and its effect on land surface temperature in Dera Ghazi Khan tells an interesting story of anthropogenic environmental transformation during the past 25 years. The results show that the local microclimate has been significantly changed by urbanization in terms of the exponentially increasing built-up surfaces (354–570 km²) which led to a significant enhancement of the Surface Urban Heat Island (SUHI) effect. This change is especially crucial because Dera Ghazi Khan is situated in an area of high thermal stress, which is a characteristic of the arid climatic zone, and the introduction of impervious surfaces adds to the environmental vulnerabilities.

Thermodynamic response of various land cover classes is important in understanding the mechanisms of thermal changes. The materials found in built-up areas have low albedo and high heat capacity, and showed high LST values consistently throughout the study, which peaked at 60°C in 2015. The strong positive relationship between NDBI and LST ($r = 0.71$), mathematically substantiated, confirmed that impervious surfaces act as good heat accumulators. On the other hand, agricultural areas and water bodies exhibited considerable cooling effects, wherein the NDVI has a negative correlation with the LST, and water bodies have a strong negative correlation ($r = -0.73$). In this context, the importance of maintaining

green and blue infrastructure in urban environments is highlighted by evapotranspiration from vegetation and water bodies' thermal inertia as natural climate regulation mechanisms.

The analysis of the variation in precipitation is an important parameter for the characterisation of the urban thermal environment. The patterns show that years with more precipitation had better vegetation health and less thermal stress whereas years with less precipitation had more thermal stress due to more built-up surface heating. The interplay between the macroclimatic conditions and the gradient of microclimatic modification due to urbanization underlines the complexity of the SUHI phenomenon and the need to take anthropogenic and natural factors into account in urban climate assessments. These results are further supported by the hotspot analysis, which shows a spatial variation of thermal hotspots from the urban core to the periphery, with cold spots consistently linked to water bodies and agriculture. These suggest that water bodies and agriculture are key zones for climate resilience; while the spatial distribution of urban heat islands was statistically supported, it did not appear to have a significant impact on the hotspot analysis results.

The methodological integration of remote sensing, GIS and statistical modelling offers a strong basis for estimating urban environmental change. Contemporary geospatial technologies such as using Google Earth Engine to process large data sets, LULC mapping using Random Forest classification, and spatial autocorrelation analysis in ArcMap illustrate the potential of geospatial technologies in urban climate research. The statistical validation for Pearson correlation and linear regression showed the expected relationships, but it also demonstrated the need to use more advanced modelling approaches in order to fully describe the urban thermal dynamics in relation to these warm and cool phenomena, as the relatively low R^2 values for some regression models indicate.

The results of this study have important implications for urban planning and climate adaptation in fast-growing secondary cities of developing countries. This has led to an unsustainable trend, as 61% of the area has been built over in the last 25 years, at the expense of the barren land and agricultural buffers. The study brings novel empirical evidence from a secondary city context, thus contributing to the literature, which has focused so far on primary megacities. This research shows that secondary cities, which have unplanned growth patterns and limited institutional capacities, can be as vulnerable as or more vulnerable than major cities with regard to UHI effects and need specific and evidence-based planning interventions to increase urban resilience and sustainability.

4.6 Recommendations

1. Urban greening programs should be done to provide more vegetation cover and less thermal stress in the heavily developed areas.
2. Protection should be given to agricultural buffer zones and urban uncontrolled encroachment should be prevented on existing green spaces.
3. Sustainable urban planning policies should focus on the controlled growth and the development of environmentally friendly infrastructures.
4. To reduce the Surface Urban Heat Island effect, cool roofs, reflective paving materials, and climate sensitive urban design should be encouraged.
5. Conservation and restoration of water bodies/ canals/wetlands on the basis of its great cooling effect in urban environment.
6. For future EA's, continuous monitoring should be done using Remote Sensing, GIS and cloud-based geospatial platforms like Google Earth Engine.

7. Local authorities need to incorporate climate adaptation measures in urban planning processes to enhance urban resilience to extreme heat events.
8. It is suggested to include higher temporal resolution datasets, socio-economic variables and advanced machine learning approaches for a deeper understanding of urban climate dynamics in further research.
9. The strategic recommendations that are proposed here are based on the empirical findings of this broad geospatial assessment to address the negative influence of urbanization on the land surface temperature and to make the environment more sustainable in Dera Ghazi Khan.
10. Urban Greening and Green Infrastructure: The negative correlation of NDVI with LST is very strong ($r = -0.50$) and is promising enough to implement systematic urban greening programs. Thermal stress can be greatly mitigated by strategically locating urban parks, green belts and roadside plantations in high-density built-up areas. Priority should go to building up a network of green corridors from existing areas of agriculture to urban centres, with continuous green areas and cooling zones that are effective in disrupting the continuity of thermal hotspots. The adoption of vertical greening systems and green roofs on commercial and institutional buildings would also work in favour of the cold island effect while conserving land.
11. Protection of Agricultural Buffer Zones: The significant overall decline in agricultural land (from 634 sq. km in 2000 to 570 sq. km in 2025) and the proven cooling effect of agricultural zones make the need to immediately ensure legal protection of peri-urban agricultural buffers urgent. Policies should be adopted that curtail unmanaged urban growth on agricultural lands, thereby keeping these areas as natural climate-regulating areas. The preservation of agricultural land has both microclimatic and food security, economic livelihood and ecological connectivity aspects. Build to the "cooling buffer" requirements, by limiting impervious surface development within a defined distance from agricultural areas, should be included in zoning regulations.
12. Climate-Sensitive Urban Design: The high thermal signatures of built-up areas (59°C maximum in 2025) must lead to a change in the approach of urban design. Cool roofing, high albedo paving materials and reflective building coatings should be required by building code and city ordinance. The planners should focus on compact and dense urban development rather than the present horizontal sprawl with emphasis on land use and its reduction. Incorporating permeable pavements, stormwater retention and water-sensitive urban design skills can help maximize evaporative cooling and minimize accumulation of surface temperature.
13. Water Body Conservation and Restoration: The conservation and restoration of the Indus river, the irrigation canals and natural wetlands should be given top priority due to the strong negative correlation between water bodies and LST ($r = -0.73$). Urban water features such as decorative ponds, rainwater harvesting features and bioswales may generate microclimates in dense urban environments. It is recommended that existing water bodies are safeguarded from encroachment and pollution in the interest of regulation of such changes and restoration programs are aimed at restoring degraded water bodies to the greatest possible benefit for their cooling capacity.
14. Future research and technological progress: The relatively low explanatory power of NDBI in regression models ($R^2 = 0.0175$) indicates the necessity for more advanced analytical methods. Future studies should investigate machine learning and deep learning techniques for more precise modeling of urban thermal dynamics, include higher temporal resolution datasets, and integrate socioeconomic factors to comprehend the social aspects

of heat vulnerability. Longitudinal studies should continue monitoring urban climate evolution, assessing the effectiveness of implemented mitigation strategies, and enabling adaptive management approaches. Developing local climate models specific to the Dera Ghazi Khan region would yield more accurate projections of future thermal conditions and guide long-term planning decisions.

4.7 Summary and Identification of the Research Gap

From an absolute point of view, the vast literature of both national and global contexts has firmly established that horizontal spread of urban areas (characterized by the substitution of natural cooling materials with impervious materials with high thermal capacity) is directly contributing to the increase of Land Surface Temperature and the ongoing intensification of the Surface Urban Heat Island effect. But there is a significant and ongoing research gap in the current literature. Most of the previous research is conducted at the primary global megacities, or in temporal snapshots with very limited time scales (e.g. 1 year against 1 other year), which are unable to capture the true time dynamic of urban microclimates.

Besides, there is a lack of a comprehensive spatial study of the effects of climate change over a long period (25 years) using GEE (cloud computing infrastructure) with precise cartographic modeling (ArcGIS 10.8) strictly on the basis of a streamlined and rigorous four-class parameterization framework (Water body, Built-up, Agriculture, Barren land) in secondary dry cities such as Dera Ghazi Khan. Most importantly, the combination of these advanced spatial methodologies with transparent, reproducible and verifiable statistical modeling directly in reachable platforms, such as Microsoft Excel, to mathematically prove the urban thermal impact is completely lacking. This study directly fills these gaps in terms of various aspects to show how a localized, highly accurate, statistically validated framework can be used for sustainable urban planning and environmental mitigation in the rapidly growing arid secondary urban centers.

5 CONCLUSION

This study outlines the results of the 25-year spatiotemporal analysis (2000-2025) of Dera Ghazi Khan, which is a comprehensive synthesis. This study combined satellite remote sensing data, Geographic Information Systems (GIS) and multivariate statistical modeling techniques, thus being able to quantify the complex relationship between the different urban expansion patterns, the Land Surface Temperature (LST) variations, the biophysical spectral indices and the precipitation variability.

Investigation about the Land Use/Land Cover (LULC) changes in last two and half decades substantiate that the Landscape architecture of Dera Ghazi Khan has undergone a profound and irreversible changes. Empirical evidence shows that the built-up environment was growing exponentially and in an orderly fashion while consuming the other land-cover classes that represent barren and semi-arid environment. This growth occurred in a carefree manner, and indicated an unchecked outward sprawling growth pattern with the rapid increase in the population and infrastructural developments far outstripping systematic and structural zoning. The drastic decrease in open surfaces (pervious) represents a direct measure of the high level of anthropogenic, that is, how anthropogenic activities have permanently modified the landscape surface from a natural and porous to an artificial and impervious one (Weng et al., 2004).

The thermal Remote sensing aspect of this study proved this development and progressive intensification of the Surface Urban Heat Island (SUHI) effect in Dera Ghazi Khan without any doubt. Spatial distribution of LST was observed to be dependent on heavily on surface characteristics: The Urban Heat Sinks: High thermal anomalies and maximum temperature

profile were found exclusively in built-up areas in the dense urban core and newly developed peripheral infrastructure, with low reflective power high-heat capacity artificial material covered the ground. The Ecological Cooling Buffers: On the other hand, agriculture fields and local water bodies were the main cooling sinks in the region. This spatial difference is mathematically demonstrated that the microclimate at local scale is directly controlled by the sensible and latent heat flux trade-off due to evapotranspiration (Voogt & Oke, 2003; Weng, 2009).

Biophysical spectral indices (Normalized Difference Vegetation Index (NDVI) and Normalized Difference Built-Up Index (NDBI)) proved to successfully decipher the quantitative processes which control the formation of urban microclimates: NDBI vs. LST: A good positive correlation was obtained between the NDBI and LST which shows that the main heat trapping materials in the city are concrete, asphalt aggregates and high-density built-up surfaces. NDVI vs. LST: The NDVI, however, showed a much tighter negative correlation with LST, confirming the importance of healthy vegetative cover in reducing LST due to shading and transpiration (Yuan & Bauer, 2007; Zha et al., 2003). Temporal precipitation analysis, in addition found macroclimatic variability as a key external regulator (precipitation interaction). Urban thermal stress was found to be affected by naturally wet years that created higher soil moisture and improved green cover conditions across the urban landscape, while the dry years had a significant effect to increase the thermal stress across the urban landscape (Voogt & Oke, 2003).

These findings related to the environment were reinforced by spatial and statistical modeling. In the Getis-Ord Gi* Hotspot Analysis spatial distribution of severe thermal stress clearly illustrates the temporal changes, where statistically significant hot spots have grown dynamically as physical infrastructure pipelines in the period 2000-2025. Blue-green infrastructure zones were confirmed as cold spots, and thus as important zones of environmental resilience. Finally, Pearson correlation matrices and regression models were used to give mathematical validation, where it was found that built-up growth is a key contributor to LST and green cover holds a very good buffering effect as a micro climate (Li et al., 2011).

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