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Spatial Assessment of Atmospheric Contamination and Urban Heat Phenomenon in Urban Centers of Sindh, Pakistan

Zainy, Sheeba Afsar,Yasmeen Anis
Department of Geography, University of Karachi, Pakistan
***Correspondance:** zainysyeda8@gmail.com, sheebanaem@uok.edu.pk, Yasmeen_rehan@yahoo.com

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Rapid urbanization and industrialization in Sindh, Pakistan, particularly in urban hubs like Karachi, have led to significant challenges associated with air pollution and the consequences of climate change. This study employs Geographic Information Systems (GIS) techniques to investigate air quality indices (AQI) in Sindh, with a focus on particulate matter such as PM2.5. This research provides a novel solution by visually illustrating the spatial patterns and potential correlations between air pollution and temperature, an area not comprehensively addressed before. By utilizing interpolation methods and graphing AQI values over time, this study identifies air-polluted areas and explores their spatial distribution throughout the year. The juxtaposition of PM2.5 concentrations with land surface temperature (LST) maps reveals spatial patterns and potential correlations. It is observed that areas with elevated air pollution levels often coincide with urban centers, exacerbating the urban heat island effect due to human activities generating excess heat. Furthermore, the impacts of air pollution extend beyond human health, affecting ecosystems, soil, water, and biodiversity. By juxtaposing PM2.5 concentrations with land surface temperature (LST) maps, this research visually illustrates spatial patterns and potential correlations between air pollution and temperature. Surface temperature maps reveal heightened temperatures in areas with significant air pollution, indicating a direct relationship between pollution levels and increased temperatures. However, the complexities of this relationship are acknowledged, as the impacts of air pollution on climate are influenced by various factors including geographic location, meteorological conditions, and pollutant composition. This study provides valuable insights into the spatial dynamics of atmospheric contamination and its implications for urban heat land formation in Sindh, contributing to a better understanding of the interplay between anthropogenic activities, air quality, and climate change.

Keywords: Air Pollution, Urban Heat Island, Climate Change, Spatial Analysis, Urbanization.

Introduction:

Urbanization, a hallmark of the 21st century, has transformed the natural environment worldwide, with over half of the world's population now residing in urban areas. This rapid urban expansion has brought about significant challenges, particularly concerning air pollution and urban heat islands (UHIs). High levels of atmospheric pollutants, including particulate matter (PM) and nitrogen oxides (NOx), originate from human activities and industrial processes, posing risks to both health and climate stability. Concurrently, the urban heat island exacerbates temperature differences between urban and rural areas, impacting various aspects including health, energy usage, and local climate patterns [1]. Addressing these global challenges necessitates thorough research to comprehend spatial dynamics and driving forces, employing sophisticated methodologies such as geographic information systems (GIS) and remote sensing.

Recent studies have highlighted the severity of air pollution and its impact on urban environments. [2] conducted a study monitoring air quality in Karachi's major industrial zones from 2020 to 2022. The study discovered that pollutant concentrations were moderate post-monsoon compared to pre-monsoon due to cyclical effects. The levels of particulate matter (TSPM, PM2.5, PM10), SO2, NO2, and CO exceeded environmental standards. Notably, North Karachi exhibited a lower risk due to its smaller industrial base. The high pollutant levels pose health risks and negatively impact plant growth and soil quality, emphasizing the need for local environmental standards to mitigate these issues [3].

The swift urbanization and industrial development in Pakistan, particularly in major urban centers like Karachi, have amplified the challenges posed by air pollution and climate change. Utilizing Geographic Information Systems (GIS) techniques, this research assesses air quality indices (AQI) in Pakistan with a focus on particulate matter such as PM2.5. Through the analysis of AQI values and the identification of areas with high levels of air pollution, this study aims to shed light on the spatial distribution of atmospheric contamination and its implications for the formation of urban heat islands [4].

Moreover, this study investigates the interplay between urban growth, atmospheric contamination, and the urban heat island effect in Sindh province, Pakistan. Urbanization in Sindh, especially in densely populated cities like Karachi, significantly contributes to air pollution [5][6]. The rapid expansion of urban areas results in increased emissions from vehicles, industrial operations, and energy consumption, all of which release pollutants into the atmosphere. Additionally, urbanization leads to deforestation and land degradation, diminishing natural barriers that help mitigate air pollution. These combined factors exacerbate air quality issues in urban centers of Sindh.

Objectives:

The objectives of this study are as follows:

- To assess the spatial distribution of air pollution in urban centers of Sindh, Pakistan_: This involves identifying areas with high levels of particulate matter (PM2.5) and analyzing the temporal variations in air quality indices (AQI).
- To examine the relationship between air pollution and the urban heat island effect_: By juxtaposing PM2.5 concentrations with land surface temperature (LST) maps, the study aims to visually illustrate spatial patterns and potential correlations between air pollution and teperature.
- To explore the impacts of urbanization on air quality and land surface temperature (LST). The study will utilize GIS and remote sensing techniques to analyze the effects of urban expansion on environmental parameters in Sindh.
- To provide insights for urban planning and environmental management: The findings will contribute to developing strategies for mitigating the adverse impacts of urbanization, focusing on pollution control and climate adaptation measures.

By achieving these objectives, the study aims to contribute to existing knowledge in the field, providing valuable insights into the spatial dynamics of atmospheric contamination and its implications for urban heat phenomena in Sindh.

World Map of Global Climate Risk Index

Study Area:

Geographically, Sindh lies between 23° 42’ North to 28° 29’ North latitude and 66° 41’ East to 71° 10’ East longitude. It is bounded by the Arabian Sea to the south, the Indian states of Gujarat and Rajasthan to the east, Punjab province to the north, and Balochistan province to the west. The Indus River runs through the province from north to south, serving as a vital water source and influencing the region's agricultural activities. Urban areas in Sindh include Karachi, Hyderabad, Sukkur, Larkana, and Mirpurkhas, among others. Karachi, the provincial capital, is the largest city in Sindh and Pakistan's primary economic hub. It is located between 24° 45' North to 25° 37' North latitude and 66° 42' East to 67° 34' East longitude, about eighty miles west of the Indus River. Karachi's surrounding areas include Dadu District to the north and northeast, Thatta District to the east, the Arabian Sea to the south and southwest, and Lasbela District (Balochistan) to the northwest [7]. Figure 1 shows World Map of Global Climate Risk Index 2000-2019.

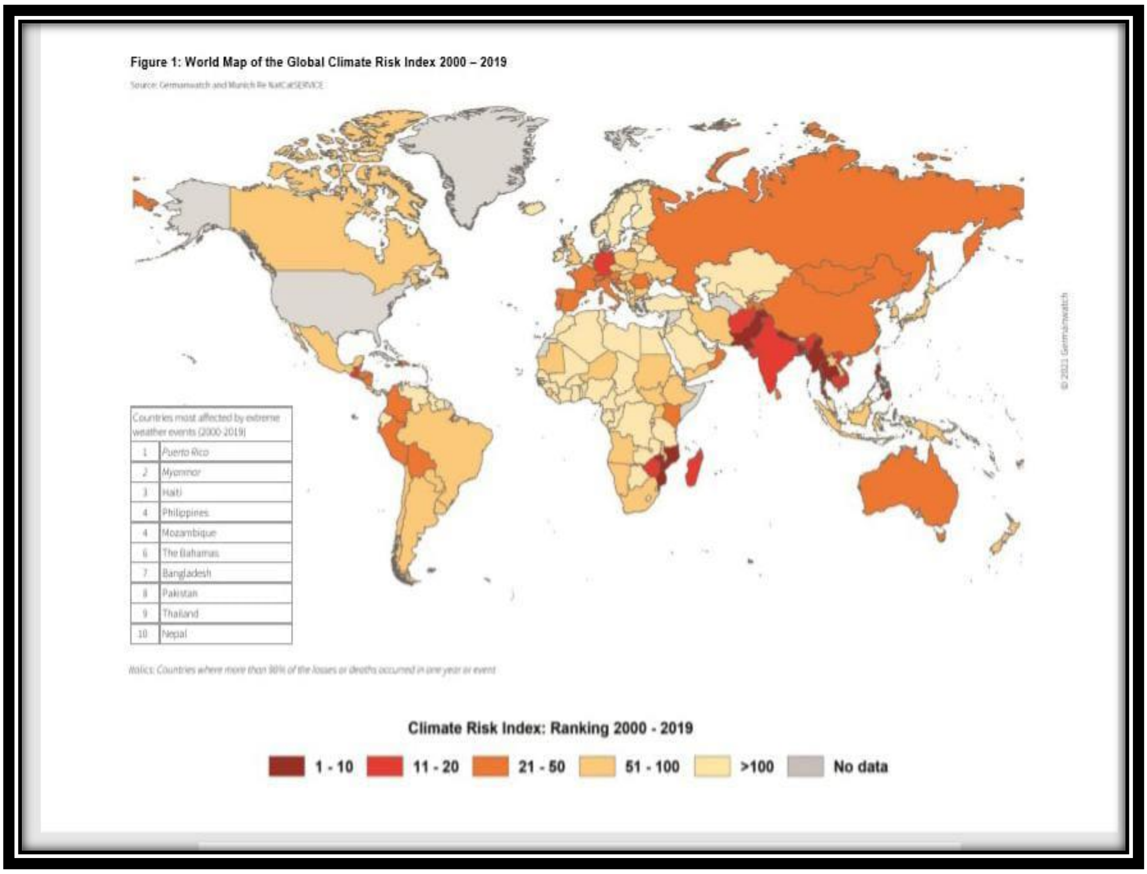

Figure 1: World Map of Global Climate Risk Index 2000-2019.

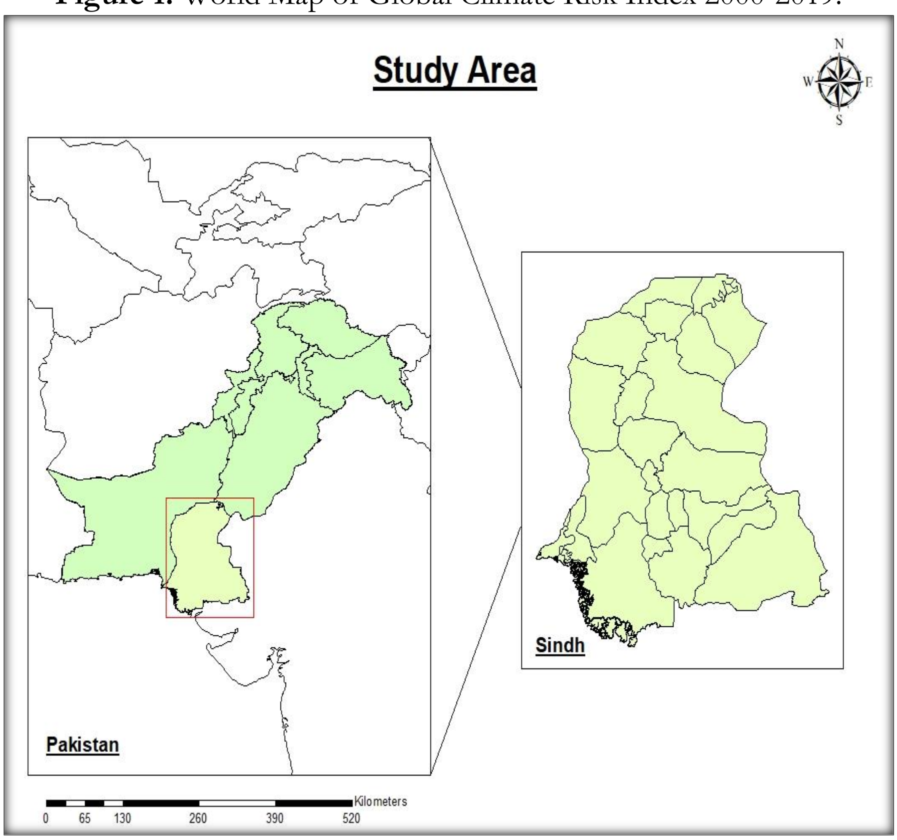

Figure 2: Study site.

Sindh's urban areas are characterized by their rapid growth and diverse populations as shown in figure 2. Cities like Hyderabad, located along the east bank of the Indus River, serve as important commercial and cultural centers. Similarly, Sukkur, situated further north along the Indus, is known for its historical significance and strategic location [8]. Overall, Sindh's urban landscape is a blend of historical heritage and modern development, facing challenges such as infrastructure development, environmental conservation, and socio-economic disparities [9].

Study Area of Sindh:

Methodology:

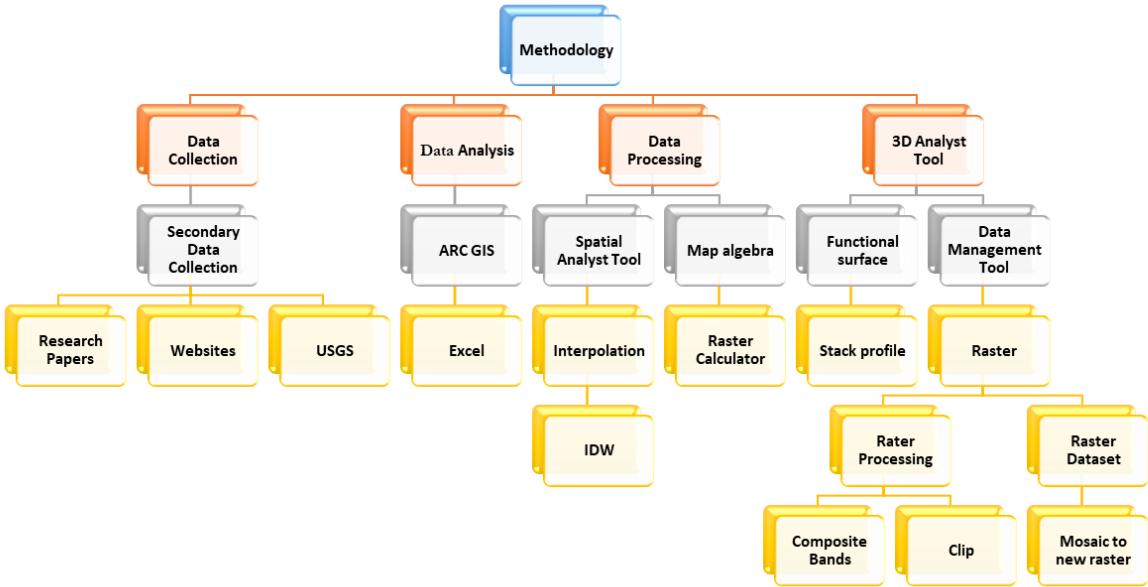

Figure 3: Flow diagram of methodology.

Figure 3 shows the flow diagram of methodology. This study utilized secondary data sources, including research papers, articles, and air quality data from IQAir, along with MODIS satellite imagery from the United States Geological Survey (USGS). The data were analyzed using ArcGIS software to perform spatial analysis and mapping, focusing on PM2.5 concentrations and Land Surface Temperature (LST) to assess the impacts of urbanization on air quality and the urban heat island effect in Sindh [10]. This study utilizes secondary data to estimate the impacts of urbanization on air quality and land surface temperature (LST) in Sindh. The data were sourced from research papers, articles, and the United States Geological Survey (USGS), with additional air quality data from IQAir. A quantitative research design was adopted to analyze spatial and environmental data, making it suitable for measuring urbanization effects [11].

Data analysis involved using ArcGIS for spatial analysis and mapping. ArcGIS is a geographic information system software for working with maps and geographic information. Air quality data, specifically PM2.5 concentrations, were interpolated to highlight areas with higher pollution levels. PM2.5 refers to particulate matter with a diameter of less than 2.5 micrometers, which is a common air pollutant. Satellite imagery was mosaicked and clipped to fit the Sindh shapefile, and LST values were converted to Celsius using the Raster Calculator in ArcGIS, creating an urban heat island map to illustrate urbanization effects. LST stands for Land Surface Temperature, a measure of how hot the land surface is to the touch. Excel was employed for data organization and preliminary statistical analysis [12].

Comprehensive datasets covering Sindh were utilized to ensure extensive spatial coverage. Ethical considerations were primarily focused on proper use and citation of secondary data sources since the research did not involve human participants. The study has limitations, including dependency on the accuracy and resolution of secondary data, potential gaps in temporal coverage, and the precision of interpolated air quality maps based on data point distribution. [13] Despite these limitations, the structured methodology ensures a systematic approach to understanding urbanization impacts on environmental parameters in Sindh, providing valuable insights for urban planning and environmental management

Results and Discussion:

This research employed MODIS Land Surface Temperature (LST) data, analyzed using ArcGIS, to examine temperature fluctuations in the Sindh region during 2023. Data from both LST Terra and LST Aqua were evaluated and converted to degrees Celsius. Figure 4 presents the LST Terra data, revealing a maximum temperature of 44.69°C and a minimum temperature of 12.83°C. This dataset offers an overview of the temperature distribution throughout Sindh, demonstrating notable spatial variation.

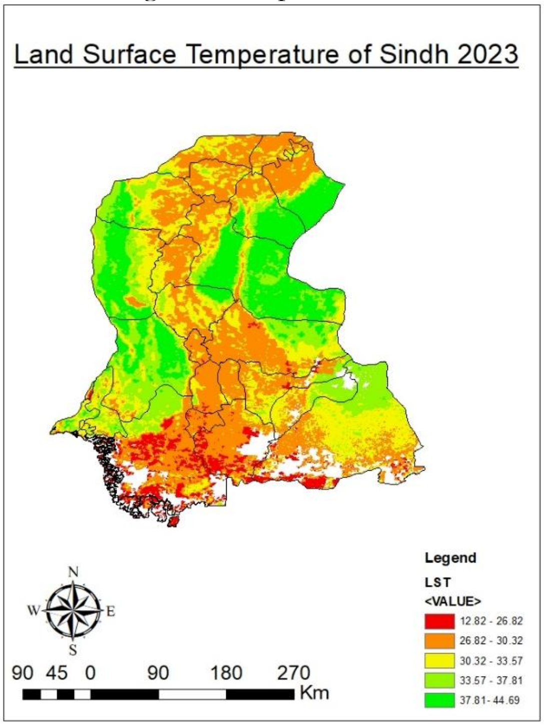

Figure 4: Land Surface Temperature (Terra) of Sindh

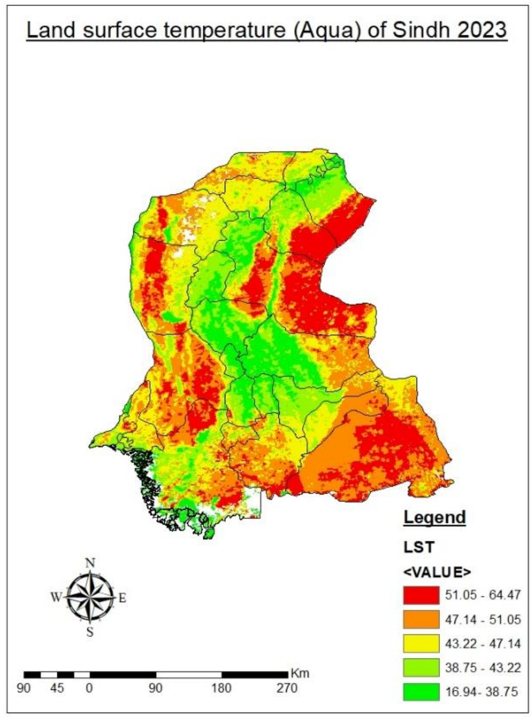

Figure 5: Land Surface Temperature (Aqua) of Sindh

In Figure 5 the LST Aqua data presents a high temperature of 64.48°C and a low temperature of 16.94°C. The increased maximum temperature observed in the Aqua dataset can be attributed to the afternoon data collection time, which typically records higher temperatures compared to the morning data collection time of the Terra dataset.

Figure 6 focuses on the Urban Heat Island (UHI) effect within Sindh, showing temperatures with a high of 37.52°C and a low of 5.66°C. This map highlights the significant temperature elevation in urban areas compared to rural regions. A key observation across all datasets is the consistently higher temperatures in urban areas compared to rural regions. This trend is attributed to the UHI effect, where urbanization leads to increased heat retention due to extensive concrete surfaces, reduced vegetation, and higher emissions. The urban areas in Sindh exhibit a marked increase in temperature, consistent with global findings on the UHI effect.

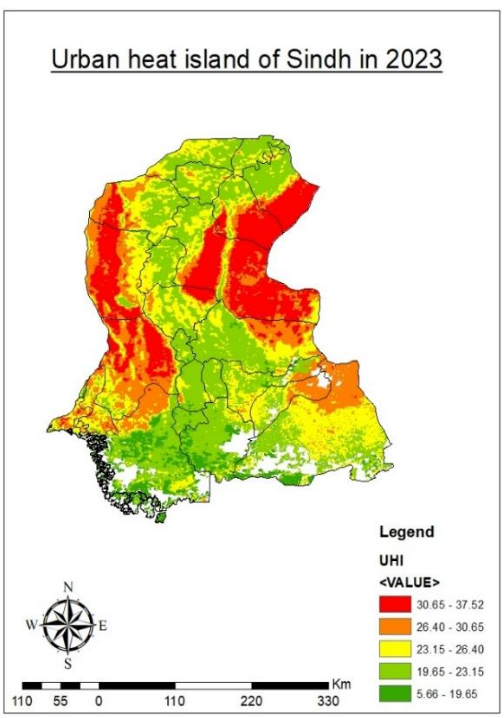

Figure 6: Urban Heat Island of Sindh 2023

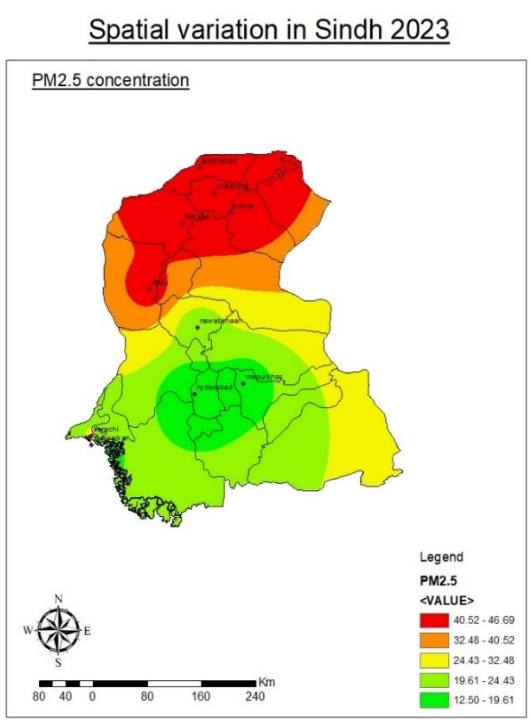

Figure 7: PM2.5 Conccentration

Additionally, spatial interpolation analysis was conducted to assess air quality in urban areas of Sindh. Data collected from IQAir was used to create maps for PM2.5 concentrations and the Air Quality Index (AQI). A point shapefile was generated specifically for urban areas to visualize air quality variations. Figure 7 displays the PM2.5 concentration levels in urban Sindh. The data indicate areas with higher pollution levels, which are critical for understanding the spatial distribution of air pollutants.

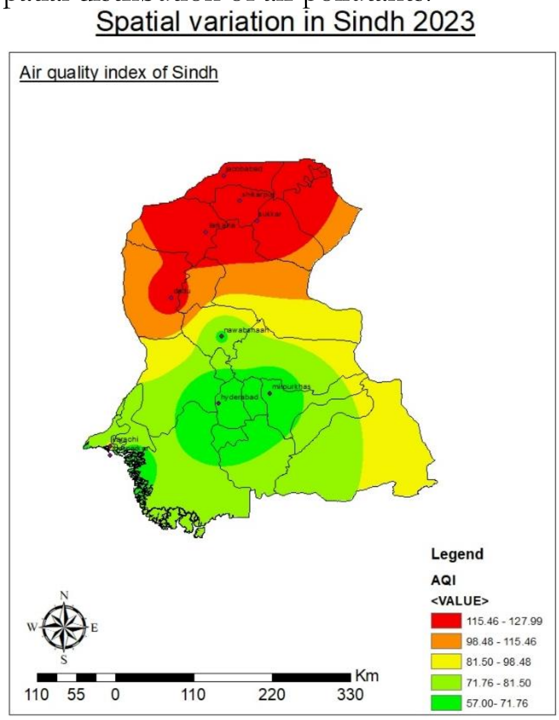

Figure 8: Air Quality Index

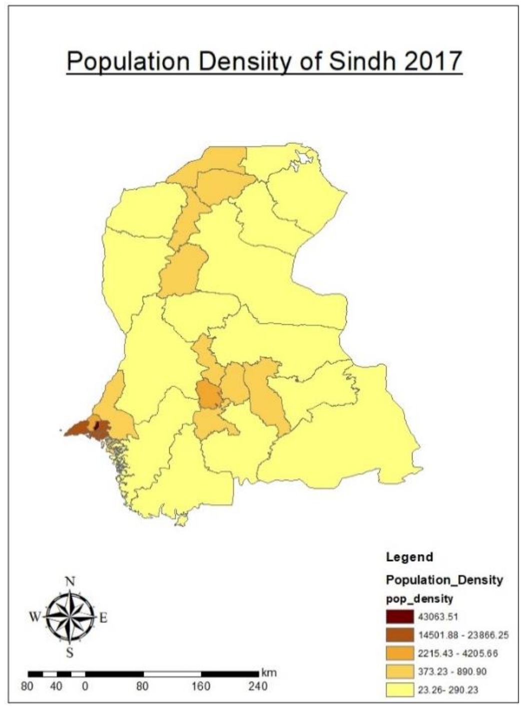

Figure 9: Population Density of Sindh 2017

Figure 8 illustrates the Air Quality Index (AQI) for urban Sindh, highlighting regions with poor air quality. The map shows that urban centers experience worse air quality, likely due to higher traffic, industrial activities, and other urban pollutants. Figure 9 presents the population density map of Sindh. This map clearly shows that urban areas, particularly Karachi, have a much denser population compared to rural areas. This high population density is a contributing factor to the observed temperature and air quality issues.

Figure 10 uses MODIS data to classify land use and land cover in Sindh. The classification includes rangeland, barren land, water bodies, built-up areas, crop irrigated, irrigated agriculture, mangroves, and orchards. The map clearly shows that built-up areas are most prominent in Karachi, highlighting the extensive urban development in this city.

These findings emphasize the importance of using remote sensing and spatial analysis to monitor environmental conditions. The distinct temperature profiles and air quality metrics observed in urban areas underline the need for targeted climate adaptation, pollution control measures, and urban planning strategies. The high population density and extensive urban development in Karachi exacerbate these environmental challenges, requiring focused intervention.

The integration of LST Terra and Aqua data, along with UHI, air quality, population density, and land use analyses, provides a comprehensive view of environmental dynamics in Sindh. This approach underscores the critical role of spatial analysis in environmental monitoring and urban management, enabling the development of more effective strategies to mitigate adverse environmental impacts in urban areas. The findings of this study align with and expand upon existing research on urban heat islands (UHIs) and air pollution in urban areas. The observed higher temperatures in urban centers of Sindh, particularly Karachi, corroborate the well-documented UHI effect, where urbanization leads to increased heat retention due to extensive concrete surfaces, reduced vegetation, and higher emissions. This phenomenon has been extensively studied in various global contexts, including cities in the United States, Europe, and Asia, indicating a consistent pattern of elevated temperatures in urban environments compared to their rural counterparts.

For instance, a study by [14] on urban heat islands in North American cities found similar temperature discrepancies between urban and rural areas, attributing these differences to the concentration of buildings, roads, and other infrastructure that absorb and retain heat. Our results showing a high temperature of 44.69°C in the LST Terra dataset and 64.48°C in the LST Aqua dataset are in line with these findings, demonstrating the significant impact of urbanization on local climate.

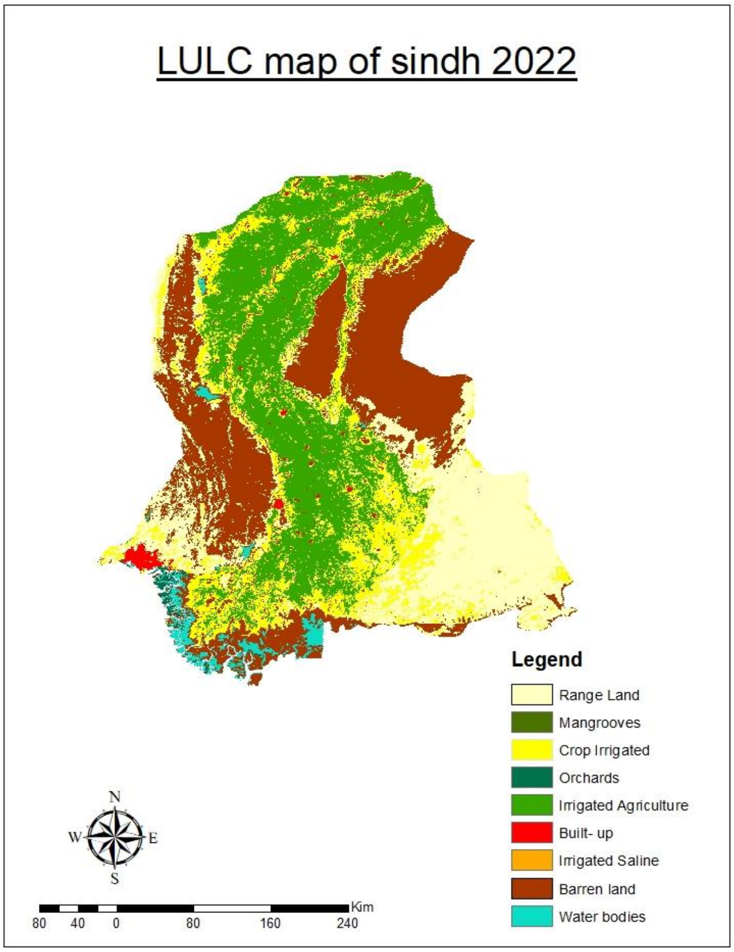

Figure 10: LULC MAP of Sindh 2022

The spatial analysis of PM2.5 concentrations and AQI in urban Sindh reveals areas with higher pollution levels, which is consistent with research conducted in other densely populated and industrialized regions. [15], in their study on air pollution in megacities of Asia, reported that urban centers with high population density and industrial activities tend to have poorer air quality due to increased emissions from vehicles, factories, and other sources. The high AQI values observed in Karachi and other urban centers of Sindh reflect similar trends, highlighting the critical need for pollution control measures.

Moreover, the use of remote sensing and GIS techniques in this study aligns with methodologies employed in previous research to monitor and analyze environmental parameters. For example, [16] used MODIS data to study land surface temperature and its relation to urbanization in Chinese cities, finding that areas with rapid urban growth exhibited significant increases in temperature. Our use of MODIS data to analyze LST and classify land use/land cover in Sindh follows this approach, providing robust and comparable results.

In terms of land use and land cover, the classification results indicating extensive urban development in Karachi are supported by studies on urban expansion in developing countries. [9] highlighted that rapid urbanization in regions such as South Asia often leads to significant changes in land use patterns, with natural landscapes being converted to built-up areas. This transformation contributes to both the UHI effect and deteriorating air quality, as seen in our study.

The findings emphasize the importance of implementing targeted climate adaptation and pollution control measures in urban areas. Strategies such as increasing green spaces, improving public transportation, and enforcing stricter emission regulations can help mitigate the adverse impacts of urbanization on temperature and air quality. Future research should continue to monitor these trends and assess the effectiveness of various interventions in reducing environmental stress in urban centers.

Overall, this study contributes to the existing body of knowledge by providing a comprehensive spatial assessment of atmospheric contamination and urban heat phenomena in

Sindh, validating our results with related research, and highlighting the critical role of urban planning and environmental management in addressing these challenges.

It is observed that areas with elevated air pollution levels often coincide with urban centers, exacerbating the urban heat island effect due to human activities generating excess heat. Surface temperature maps reveal heightened temperatures in areas with significant air pollution, indicating a direct relationship between pollution levels and increased temperatures. By juxtaposing PM2.5 concentrations with land surface temperature (LST) maps, this research visually illustrates spatial patterns and potential correlations between air pollution and temperature.

Conclusion:

The comprehensive analysis of MODIS Land Surface Temperature (LST) data, air quality measurements, population density, and land use classifications reveals significant environmental dynamics in the Sindh region, particularly in urban areas like Karachi. The study highlights the pronounced Urban Heat Island (UHI) effect, with urban areas consistently exhibiting higher temperatures due to extensive concrete surfaces, reduced vegetation, and higher emissions.

Spatial interpolation analysis of air quality data indicates that urban centers experience elevated PM2.5 levels and poorer air quality, likely driven by dense population and industrial activities. The population density map further corroborates that urban areas, especially Karachi, have significantly higher population densities, which contributes to the environmental challenges observed. The land use and land cover classification map provides critical insights into the distribution of various land types across Sindh, underscoring the extensive built-up areas in Karachi. This urban expansion correlates with the environmental issues of higher temperatures and poor air quality.

These findings underscore the need for targeted climate adaptation strategies, pollution control measures, and sustainable urban planning. Future research should focus on longitudinal studies to monitor these trends over time and assess the long-term impacts of urbanization on regional climate and air quality. The integration of remote sensing data and spatial analysis tools proves invaluable in environmental monitoring and management, providing a robust foundation for developing effective mitigation strategies to address the adverse impacts of urbanization in Sindh.

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