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Assessing the Impact of Urban Expansion on the Urban Environment in Riyadh City (2000–2022) Using Geospatial Techniques

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Abstract: The assessment of the urban environment is a crucial area of interest for the international community, particularly for the Kingdom of Saudi Arabia. Achieving environmental sustainability is among the goals of Saudi Vision 2030. Riyadh has recently witnessed urban expansion due to population growth, which can cause negative environmental effects unless this growth is accompanied by the development of appropriate environmental regulations and controls. Therefore, this study aimed to assess the city of Riyadh's urban environment and its relationship to urban expansion over time. The Thermal Environmental Index (TEI), consisting of five indicators (vegetation index, urban index, moisture index, dry index, and temperature index) was constructed utilizing geospatial techniques. Pearson's correlation analysis was performed to determine the relationship between urban expansion and urban environmental conditions. The main results show that the size of Riyadh's urban clusters doubled by 2022, increasing by 106% compared to in 2000. The results also show that, in 2000, 2013, and 2022, areas of poor environmental conditions were mainly distributed in urban areas, whereas areas with excellent and good environmental conditions were located outside of urban areas in the northern and western parts of Riyadh. Areas with good environmental conditions continued to decline, whereas areas poor environmental conditions increased from 4%, or 240 km², in 2000 to 11% in 2022, reaching 658 km². The correlation analysis clearly showed a very strong relationship between urban expansion and the deterioration in urban environmental conditions.

Keywords: urban expansion; urban environment; geospatial technologies; remote sensing; Thermal Environmental Index



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1. Introduction

The world is increasingly moving towards urbanization, with about 54% of the world's population living in cities, and this percentage is expected to rise to 66% by 2025 [1]. If the trend of people moving towards cities and their desire for urban life continues, urban areas are expected to double by 2030 [2]. As such, urbanization is one of the most prominent and important contemporary issues. Although urbanization poses a challenge to humanity, especially in terms of the environment's ability to meet its requirements, it also represents an important opportunity to develop and implement planning policies to create livable cities that are more sustainable in the long run [3]. The increasing demand for urban spaces and the significant increase in population contributes to increasing rates of urban sprawl, as urban areas begin to expand at the expense of agricultural lands or open spaces on the outskirts and suburbs of cities. The internal density of cities also increases as urban uses extend at the expense of other uses and vegetation cover [4].

Urban sprawl refers to development that extends beyond a city's core at a much faster rate than normal urban growth. The key difference between urban sprawl and regular urban growth is the excessive and unsustainable nature of sprawl. [5]. Urban sprawl has many benefits and advantages, as it contributes to accelerating the process of social

and economic development, helps improve livelihoods, and promotes the development of services. However, at the same time, it leads to many negative repercussions on the environment and its natural resources, with the rapid expansion of urban scale increases the bearing pressure of soil and water resources, and the substantial increase of infrastructure construction also aggravates industrial pollution [6]. The environment is the most affected element, as urban sprawl negatively affects ecological services, which are the benefits that humans derive from the environment such as energy, water, and other resources [7]. Along with increasing demand for resources, the urban form is a driver for GHG emissions and global warming; urban sprawl also contributes to the decline and shrinkage of vegetation cover areas, resulting in major effects on temperature, soil, and other environmental factors [8].

Since the economic boom witnessed by the Kingdom of Saudi Arabia in the 1970s, urbanization processes began to increase as the percentage of urban population rose rapidly from 17.5% in 1955 to 65.9% in 1980 and 88.5% in 2005 [9]. Urban sprawl in most Saudi cities has contributed to many environmental problems, such as pollution and depletion of natural resources [10]. In addition, urban sprawl has caused many changes to the Earth's surface, such as vegetation cover areas, moisture, water quality, and evaporation rates. Although the country is affected by natural and climatic fluctuations, human and urban activities have also greatly affected the country and its environmental characteristics [11]. Riyadh is one of the most important Saudi cities and has witnessed tremendous growth as its population has increased, and its urban areas have expanded significantly with substantial urban sprawl towards its outskirts and surrounding cities [12]. The rate of urban sprawl reached 82.9% between 1987 and 2017 [13]. Consequently, the steady population and urban growth have led to population congestion in certain areas, threatening to increased negative environmental impacts unless this growth is accompanied by appropriate environmental regulations and controls [14].

This research endeavors to evaluate the impact of urban sprawl on the urban environment of Riyadh from the year 2000 to 2022. To facilitate this objective, the study introduces the Thermal Environmental Index (TEI), a metric designed to measure and assess the prevailing environmental conditions. The TEI will serve to identify and recommend interventions to address and mitigate environmental challenges emanating from urban expansion. Furthermore, this index will augment our comprehension of the characteristics of urban growth in Riyadh, its ramifications on urban environmental constituents, and its holistic impact on the environment.

2. Literature Review

2.1. Impact of Urban Sprawl on Vegetation Index

Urban sprawl primarily impacts agricultural lands, as expansion typically occurs at their expense. When assessing the effect of urban sprawl on vegetation indices or cover, the authors of [12] found a decline in natural vegetation similar to observations made by the authors of [8,15]. However, the study in [8] excluded city centers from its analysis, and these studies varied in their scope and methodologies for assessing urban sprawl's impact. Specifically, ref. [12] analyzed the impact on agricultural lands in Riyadh using a historical, descriptive approach, showing that urban sprawl affects open natural spaces and reduces agricultural lands. In contrast, ref. [8], which focused on China during the first eighteen years of the twenty-first century, utilized the Normalized Difference Vegetation Index (NDVI) to track changes in urban areas and natural vegetation cover. This study revealed a significant deterioration in vegetation cover in urban areas, but city centers showed improved vegetation levels, attributed to targeted efforts to enhance green spaces, reflecting the efficiency and effectiveness of urban design.

Similarly, ref. [15] explored the impact of urban sprawl in Mankato, USA, on the local environment using both a descriptive historical approach and an analytical method involving high-precision remote sensing techniques to process photographic images. This study concluded that urban sprawl resulted in a 14.3% increase in the percentage of

impervious surfaces in urban areas, closely mirroring the land coverage of agricultural and grassy areas, which stood at 15.1% in Mankato. Additionally, the study highlighted the significant effects of urban sprawl on local surface runoff and water quality, underscoring the broader environmental consequences of expanding urban footprints.

However, the findings of [16] affirmed those of [8], indicating that the impact of urban sprawl is not uniformly clear and varies significantly from region to region. The authors of [16] reached this conclusion by employing a land change modeler (LCM)–Markov chain model to analyze observed data and determine the model’s coefficients. Additionally, the study utilized predictive models to simulate urban expansion through 2030. These simulations revealed substantial variations in the expected spatial structure by 2030, highlighting how rapid urban expansion and the effectiveness of planning policies significantly affect planned development outcomes.

Regarding the impact of urban sprawl on agricultural lands, the findings from [17], conducted in Al-Ahsa, Saudi Arabia, align with those of [18]. Both studies show that agricultural lands most affected by urban sprawl are those located near main roads. This proximity to major transportation routes likely makes these lands more susceptible to being developed, as they offer easier access and higher visibility, factors that typically attract urban expansion.

2.2. Impact of Urban Sprawl on Moisture Index

Climate change has become one of the most worrying problems for societies at the international and local levels in recent decades. Scientists agree that the increase in temperatures and sudden climate changes pose immediate and long-term risks to the environmental and urban composition of societies and citizens. Evidence indicates that one of the causes of climate change is urban sprawl [19]. When discussing the impact of urban sprawl on the moisture index, the conclusion of [20] is similar to that of [21]. The results of [20] showed that rapid urban sprawl in Baghdad negatively affected the region’s climate. The relationship between urban sprawl and relative humidity in the city of Baghdad was identified using remote sensing images and data downloaded from the European Center for Medium-Range Weather Forecasts (ECMWF) for the city of Baghdad, analyzing several factors, such as relative humidity (RH), temperature (Ta), and evaporation, and confirming the changes observed in urban areas. Landsat-5 and Landsat-8 images were processed and analyzed from 2010 to 2020. This study proved that there is a clear relationship between urban sprawl and relative humidity rate, as well as the rise in temperatures in urban areas. The impact of relative humidity levels on the local climate of Baghdad city from 2010 to 2020 was assessed, showing that the cumulative build-up increased from 19.60% to 27.44%. Meanwhile, based on the NDVI calculation, the healthy vegetation cover almost disappeared, with its ratio dropping from 0.05% to 0.00.

The findings of [21], which was conducted in the urban agglomerations of Beijing, Tianjin, and Hebei, contributed to understanding the impact of urban sprawl on atmospheric moisture. Observations from 133 weather stations were used to analyze the long-term trend of atmospheric moisture and the effect of urban sprawl during the period of 1961–2014. The impact of urban sprawl on atmospheric moisture was assessed by calculating differences in atmospheric moisture trends between urban and rural series. The results showed that urban areas were characterized by lower relative humidity, water vapor pressure, and specific humidity and increased vapor pressure deficit. The moisture trend was more pronounced ($p < 0.05$) in spring and autumn, while a relatively weaker trend occurred in summer and winter.

2.3. Impact of Urban Sprawl on Dry Index

Urban sprawl also affects soil and its moisture content and elements. The findings of [22–24] are consistent in terms of the impact of urban sprawl on soil and its components. The authors of [22] pointed to the impact of urban sprawl on soil, as they examined the relationship between urban sprawl and the level of soil dryness and degradation in Greece.

They examined the soil condition during the period of 2000–2010, and their study indicated that suburbs that witnessed intensive urban sprawl during this period had arid soils lacking in elements, making them of lower quality than other areas that witnessed less intensive urban expansion.

In addition, activities associated with urban growth lead to soil degradation, as these activities compress, transport, and pollute soils, thereby disturbing the local soil ecosystem and impacting its quality, as confirmed by a previous study [23]. That study aimed to examine the impact of urban sprawl on soil resources and properties, including available water storage, agricultural productivity, and soil organic carbon, in central Arkansas from 1994 to 2030. The results showed that all of these characteristics deteriorated with increasing levels of urban sprawl in the area, and the deterioration in soil quality in this area is expected to increase with urban expansion by 2030.

Urban sprawl also contributes to soil erosion and degradation, as demonstrated by [24], which aimed to determine the effect of urban sprawl on soil erosion and degradation in Inner Mongolia between 2000 and 2010. Two empirical equations were used, the Revised Universal Soil Loss Equation and the Wind Erosion Equation, to estimate soil erosion intensity. Linear regression was used to model changes in soil with increasing urban sprawl.

2.4. Impact of Urban Sprawl on Temperature Index

Examining the impact of urban sprawl on temperatures, the findings of [25] are similar to the findings of [26]. The findings of [25] showed that, as urban areas increased in Riyadh, the surface temperature also increased, according to satellite imagery data. In April 1985, it was 11.5 °C, while in 2000, it reached 27.5, and in 2016, it reached 30 °C. There was a moderate positive correlation of 0.68, although it was not significant since the *p*-value (0.517) was greater than 5%, suggesting an effect of urban sprawl on rising temperatures.

However, ref. [26] monitored changes in heat islands in Yanbu City using Landsat satellite imagery data. This study followed the methodology of spatial analysis of satellite imagery data based on a set of mathematical algorithms specific to Landsat. The methodology involved processing imagery data to derive spectral radiation layers and then temperatures from the thermal infrared bands, as well as classifying the layers to identify hotspots and areas of concentration of heat islands and their changes over time in Yanbu City. The research results showed an increase in the average temperature in the city from 31.75 in 2001 to 32.54 in 2010 and 35.24 in 2019. The area of heat islands with temperatures above 35 increased from 0.72 km², at a rate of 0.22% of the total area of the city, in 2001 to 11.23 km², at a rate of 3.43% of the total area of the city, and from 2010 and 198.6 km², at a rate of 60.63% of the total area of the city, in 2019. The pattern of distribution of heat islands changed over time due to urban development and changes in land use, which affected the spectral radiation and temperatures derived from the imagery data.

2.5. Using Urban Environmental Assessment Indicators

Integrated environmental indices constitute one of the most important modern indicators used to assess the environmental situation in urban areas, and such indices have been used in many studies. In [27], which aimed to identify the environmental situation in Semarang, Indonesia, and determine the impact of urban sprawl density on urban environmental quality, remote sensing data (Landsat TM/ETM and Landsat-8 OLI) were relied upon. To assess the urban environment, an integrated environmental index was used, which was composed of four sub-indicators, namely, greenness, moisture, dryness, and cumulative clustering.

The results showed that the urban area increased by an average expansionary area of 3.9 km² in the period of 2005–2015. The study also showed that the deterioration in the urban environmental situation of Semarang City spread in a pattern towards the west, southeast, and east of the city, where the lowest integrated environmental index score was found in the central and northern parts. Thus, the negative impact of increased density of urban sprawl on the urban environmental condition is evident. The authors of [28]

used the Remote Sensing Ecological Index (RESI) to assess environmental quality by using multi-temporal Landsat images to extract the four indicators of moisture, vegetation cover, temperature, and dryness, and then the RSEI was calculated using principal component analysis. The results showed that the environmental quality of Enke City decreased from 1999 to 2019 and then increased slowly from 2009 to 2019. The area in which the ecological quality improved during the period from 1999 to 2009 constituted 18.31% of the urban area, while the worst ecological area represented 29.68% of the urban area. The authors of [29] developed an Urban Environmental Quality Index (UEQI) based on remote sensing data, and five environmental indices were derived from Landsat OLI images, namely, the Modified Normalized Difference Impervious Surface Index (MNDISI), the Modified Normalized Difference Water Index (MNDWI), the Normalized Difference Vegetation Index (NDVI), the Normalized Difference Built-Up Index (NDBI), and the Soil-Adjusted Vegetation Index (SAVI), using principal component analysis (PCA). The Urban Environmental Quality Index was calculated for seventeen communities in Casablanca. The UEQI values were spatially assigned to three categories (good, moderate, and poor). The results showed that the environmental quality is inadequate in communities with less green space and more impervious surfaces. The results of this work could serve as an effective tool to identify the most important interventions that should be carried out by the authority for present and future urban planning and land management.

Previous studies have separately addressed the impact of urban expansion on vegetation cover and thermal conditions, as well as its effect on moisture and drought indicators, using geospatial techniques. Some studies, such as those by [28,29], focused on assessing urban environmental quality using an environmental quality index without considering urban expansion. Meanwhile, other studies, like those conducted by [27], primarily focused on evaluating urban environments using an integrated environmental index consisting of four indicators (greenness, moisture, drought, and cumulative clustering). The study by [30] applied the same integrated environmental index (IEI) and, by comparing it with temperature, revealed a negative correlation illustrating the effects of the environmental index on land surface temperature (LST). These two studies could be utilized to construct an index assessing the environmental condition in Riyadh. This study distinguished itself by adding a temperature indicator due to the hot desert region of the study area. Hence, the Thermal Environmental Index (TEI) was introduced to evaluate the urban environment and provide results that are in line with the nature of the region. It can be applied over time to study the impact of urban expansion on the urban environment and its components.

3. Study Area

Riyadh is the capital of Saudi Arabia, which is located at latitudes ($24^{\circ}23'07''$ – $25^{\circ}0'20''$ N) and longitudes ($46^{\circ}27'57''$ – $46^{\circ}55'14''$ E), as shown in Figure 1, with an elevation of about 600 m above sea level (Riyadh Municipality, 2017). The climate of Riyadh is characterized as that of an arid desert with high summer temperatures and low winter temperatures, ranging around 42°C in the summer and about 11°C in the winter [31]. It is one of the fastest-growing cities in the world, causing many challenges at the social, economic, and environmental levels. Riyadh's population growth rate for the year 1438 AH was 4%, which was very high compared to the global average of 2.5%. This growth poses challenges in terms of provision of housing, services, facilities, and job opportunities to avoid urban crises that may arise as a result of this high rate of population growth.

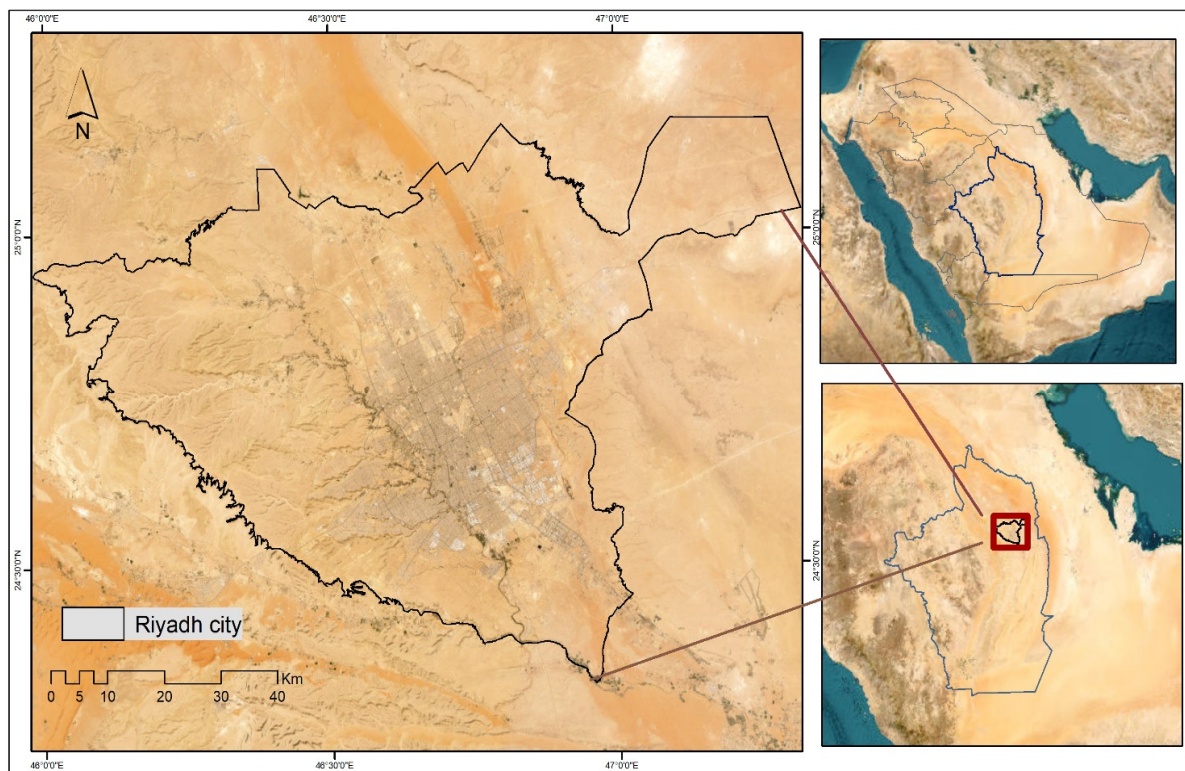


Figure 1. Study area.

4. Data Preparation

4.1. Types of Data and Sources

In this study, data were used from several sources.

4.1.1. Remote Sensing Data

Remote sensing data were obtained from the website of the United States Geological Survey (USGS) Landsat satellite missions. These missions, launched by the National Aeronautics and Space Administration (NASA) and the USGS, aim to monitor the Earth and collect data and images for research on global changes in agriculture, urbanization, and other applications [32].

Satellite imagery data for the year 2000 were obtained from the Landsat-5 satellite, which contains two sensing systems. The first system is the thematic mapper (TM) sensor, which records radiation across seven spectral bands. Three of these bands are within the visible spectrum, and the remaining bands are within the infrared spectrum. The second system is the multispectral scanner (MSS) sensor, which records radiation across four spectral bands.

Additionally, satellite imagery data for the years 2013 and 2022 were obtained from the Landsat-8 satellite. This satellite was launched in February 2013 and scans the entire Earth every 16 days. It includes new sensors such as an operational land imager (OLI) and a thermal infrared sensor (TIRS), which contain a total of 11 bands.

4.1.2. Cartographic Data

The boundary map for development protection was obtained from the Royal Commission for Riyadh City for the year 2017.

4.2. Data Collection and Processing

This stage involved collecting satellite imagery data from the USGS website for the years 2022, 2013, and 2000, starting in the month of August. Then, the data were processed to prepare them for analyses using geographic information system software (ArcGIS

Pro 3.2); for example, geometric correction of imagery was performed, mosaics were created, and imagery was clipped to the boundaries of the study area.

5. Study Methodology

This study followed an analytical descriptive approach to analyze and describe the changes that occurred in the environment of Riyadh over the years [33] and their relationship to urban sprawl. It used an experimental method to identify the causal relationship between variables [34], including using the Thermal Environment Index (TEI) to assess the urban environment. To determine the correlation between urban sprawl and the urban environmental conditions, quantitative analysis was performed.

5.1. Study Procedures

The study procedures consisted of data collection and processing, followed by data analysis and an assessment of urban environmental conditions, as shown in Figure 2.

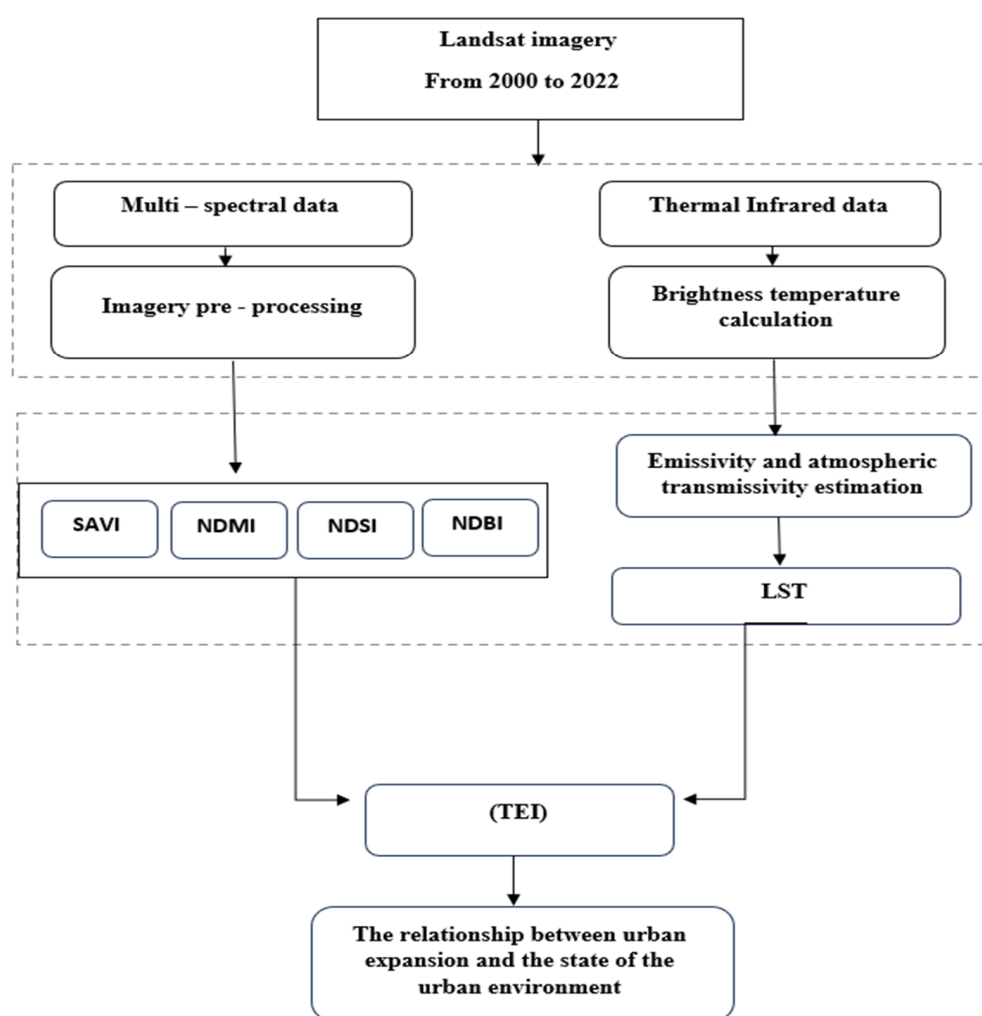


Figure 2. Study methodology.

5.2. Analysis of Indicators (Vegetation Cover, Urban Index, Dryness, Moisture, and Surface Temperature)

A quantitative analysis was performed using the satellite imagery data to obtain results for each of the five indicators (vegetation cover, urban index, dryness, moisture, and surface temperature), as shown in Table 1. Several studies such as [27,30] assessed the state of the urban environment using four indicators. In this study, five indicators were used to assess the state of the urban environment of Riyadh.

Table 1. Statistical equations for the indicators used in this study.

Index	Equation	Source
NDBI	$NDBI = (SWIR1 - NIR) / (SWIR1 + NIR)$	[35]
SAVI	$SAVI = (NIR - RED) / (NIR + RED + L)(1 + L)$, where $L = 0.5$	[36]
NDMI	$NDMI = (NIR - SWIR2) / (NIR + SWIR2)$	[27]
NDSI	$NDSI = (BSI + NDISI) / 2$ $BSI = (SWIR1 + RED - BLUE - NIR) / (SWIR1 + RED + BLUE + NIR)$ $MNDWI = (GREEN - SWIR1) / (GREEN + SWIR1)$ $NDISI = (TIR - MNDWI + NIR + SWIR1/3) / (TIR + MNDWI + NIR + SWIR1/3)$	[27]
LST	Derivation of spectral radiation based on TOA radiation	$Ly = ML \times Q_{cal} + AL - Q_i$
	Convert spectral irradiance to brightness temperature	$BT = (K2 / \ln((K1/Ly) + 1)) - 273.15$
	Derivation of vegetation index	$NDVI = (B5 - B4) / (B5 + B4)$
	Percentage of vegetation cover	$PV = \text{Square}(NDVI - NDVI_{min}) / (NDVI_{max} - NDVI_{min})$
	Spectral emissivity values	$E = 0.004 \times Pv + 0.986$
	Temperature	$LST = (BT / (1 + (0.00115 \times BT / 1.4388) \times \ln(E)))$
	Convert temperature into an index	$T = \sqrt{\frac{C}{10}} + 0.1$

5.3. Developing the Thermal Environment Index (TEI)

Principal component analysis (PCA) was used based on [27,30] to construct the TEI as follows:

$$TEI = 1 - \sum ai(PC)i$$

where $\sum ai(PC)i$ represents the sum of the main components of the indicators.

5.4. Determining the Relationship between Urban Sprawl and Urban Environmental Conditions

Statistical analysis was performed to obtain the Pearson correlation coefficient in order to determine the positive or negative relationship between two variables. The correlation coefficient always falls within the range of (+1) to (−1) [38].

6. Analysis and Results

6.1. Vegetation Cover Index (SAVI)

The SAVI was used to extract the vegetation cover area of the study area during specific time periods (2000, 2013, and 2022), as shown in Table 2.

Table 2. Vegetation cover in different time periods.

Vegetation	2000	2013	2022
Area with dense vegetation	32 km ²	24 km ²	18 km ²
Area with less vegetation density	89 km ²	79 km ²	86 km ²

To determine the vegetation cover area of Riyadh city in the year 2000, satellite imagery data obtained from Landsat-5 for the year 2000, with an accuracy of up to 30 m, were used. Figure 3 shows that agricultural areas spread over an area of 121 km² and are concentrated around the banks of Wadi Hanifa and uninhabited areas. The imagery data obtained from Landsat-8, with an accuracy of 30 m, were analyzed for the year 2013 following the same method, and the results are shown in Figure 3. The vegetation cover area reached about 103 km², indicating a decrease of 15% from what was observed in the year 2000. Excessive

human practices have exploited this natural resource, which led to its deterioration. Such practices included logging, overgrazing, and urban sprawl [39]. As for the vegetation cover area in the year 2022, imagery data obtained from Landsat-8 were analyzed following the same method, and the results are shown in Figure 3. The vegetation cover area reached 104 km², indicating an increase of 8%, with the highest percentage in areas with a low vegetation density, as shown in Table 2. The main reason for this increase in the percentage of green areas in Riyadh is the Riyadh Green Project, which is one of the major projects contributing to achieving the goals of Saudi Vision 2030 [14].

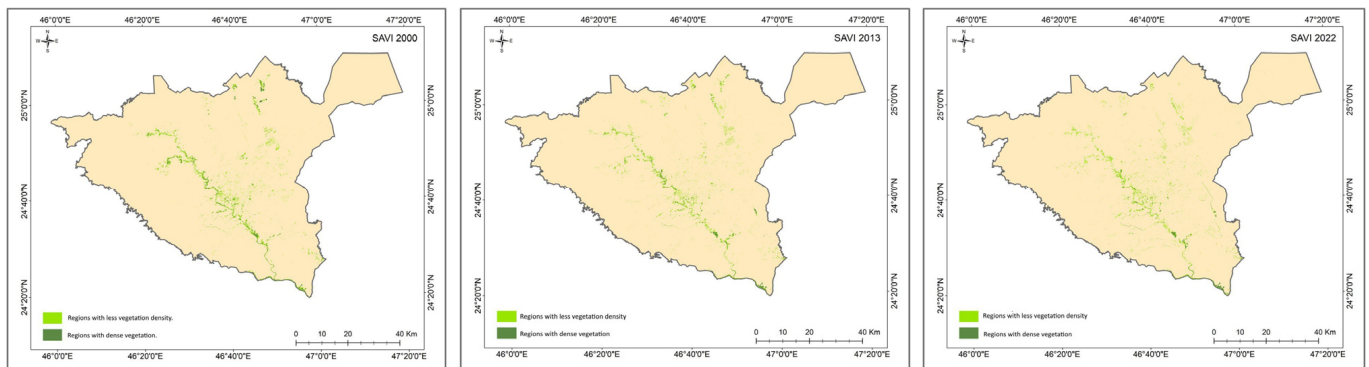


Figure 3. Vegetation cover index in 2000, 2013, and 2022.

6.2. Urban Index (NDBI)

Tracking the urban sprawl of a city is very important to uncover the geographical conditions that contribute to the emergence and development of the city over time. Modern technologies have helped monitor urban sprawl. This study analyzed satellite imagery data to deduce the urban growth boundaries of Riyadh in the years 2022, 2013, and 2000. The urban clustering area in the year 2000 was about 654 km², while in the year 2013, the area was about 1003 km². In the year 2022, the urban clustering area increased to 1349 km², showing an increase of about 346 km² compared to the previous time period at a growth rate of 34% (Figure 4). The primary direction of urban growth is clearly towards the north, followed by the west. According to the findings in [13], the reasons for this northward and northeastward urban expansion are the absence of natural or human-made obstacles in those directions. Conversely, the western side experiences relatively less growth due to the presence of natural obstacles such as Wadi Laban and Namar.

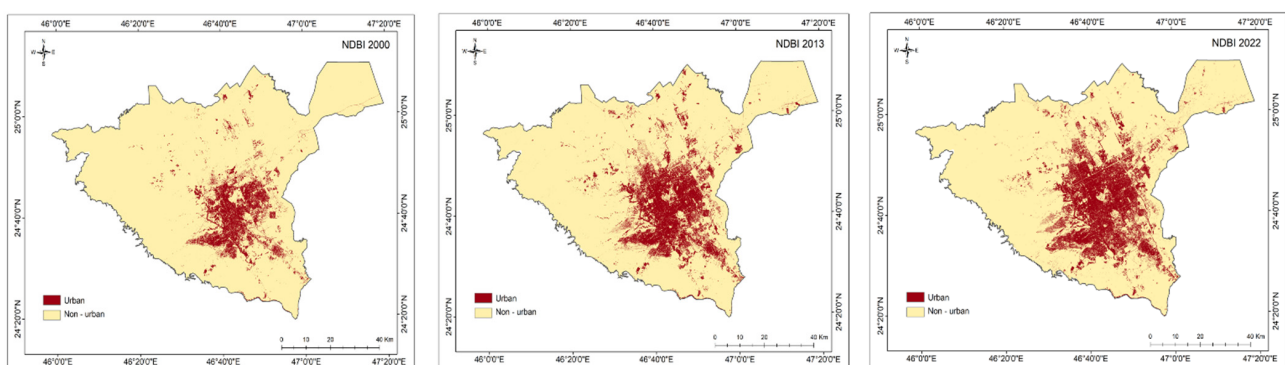


Figure 4. Urban index in 2000, 2013, and 2022.

The reason behind this urban sprawl is likely the increasing population, which is largely caused by high fertility and internal and external migration rates. The results of [40,41] showed that population growth is continuously increasing, as it increased in the year 2022 to 7,009,120 people, indicating an increase of more than 1.8 million people

compared to the year 2010, as shown in Table 3. The total number of housing units increased between the years 2010 and 2022, with the increase estimated at 1.5 million.

Table 3. Population and housing data (source: Saudi Census, 2022, and General Authority for Statistics, 2010).

Year	Population	Number of Dwellings
2004	4,088,469	717,381
2010	5,254,560	857,764
2022	7,009,120	2,426,816

6.3. Moisture Index (NDMI)

The NDMI (Normalized Difference Moisture Index) reflects the moisture content in soil and vegetation cover [42]. This index reveals the moisture levels in vegetation cover, as it is based on near-infrared and shortwave infrared bands from the electromagnetic spectrum. The values of this index range between 1 and -1 , with positive values representing areas of high moisture and negative values representing low moisture areas suffering from dryness. It is evident in Figure 5 that the areas with high moisture in the years 2022, 2013, and 2000 were spread over residential and agricultural areas.

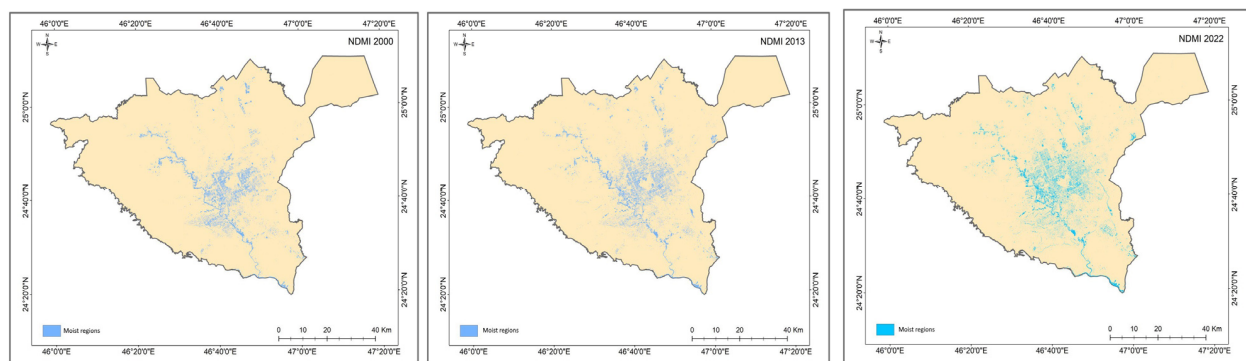


Figure 5. Moisture index in 2000, 2013, and 2022.

6.4. Dry Index (NDSI)

The Normalized Dry Soil Index was used to identify exposed bare soil. It was calculated by taking into account the NDSI to identify the distribution of bare land, as this index determines the degree of dryness [43].

As shown in Figure 6, we found a high percentage of dry areas, which is attributed to the continental desert climate of the region, which is characterized by dryness in the summer with unreliable rainfall [44]. Accordingly, we found that the dry areas are generally distributed in the city and concentrated in residential areas.

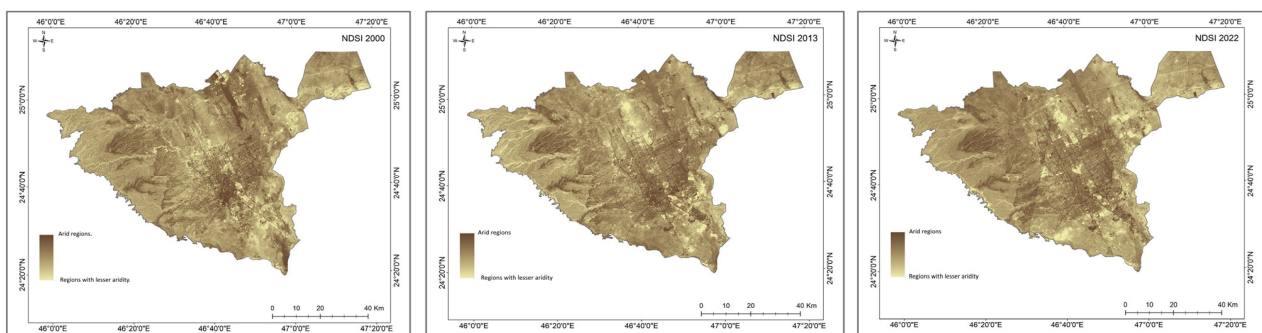


Figure 6. Dry index in 2000, 2023, and 2022.

6.5. Land Surface Temperature (LST) Index

Land surface temperature (LST) is considered one of the most important aspects in climate studies and is an important factor when studying topics such as global climate change, hydrological and agricultural processes, and urban land use [45].

The LST index was used to extract surface temperatures during the summer. It is evident in Figure 7 that the average temperature was 45 °C in the year 2000, increased to 48 °C in the year 2013, and then decreased in the year 2022 to 42 °C due to the unusual rains that occurred in that summer [46].

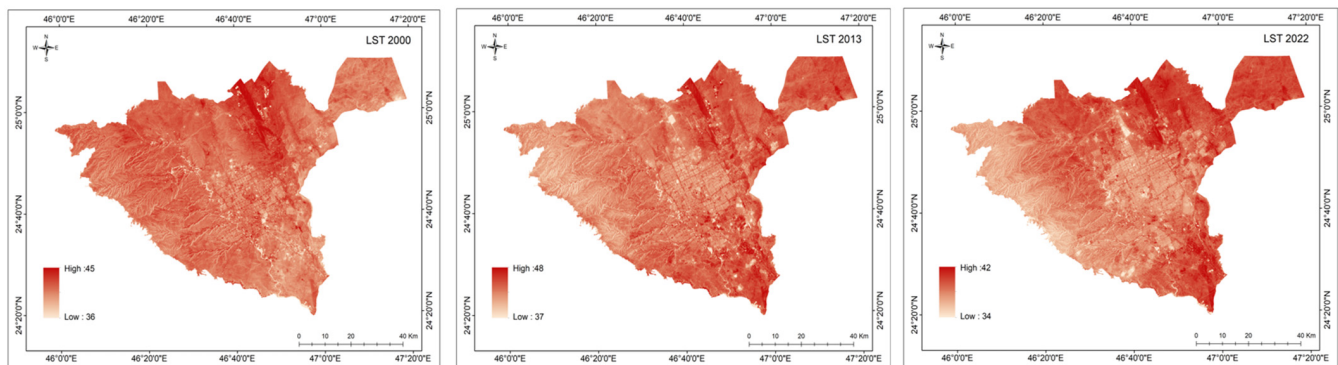


Figure 7. Land surface temperature index in 2000, 2013, and 2022.

6.6. Principal Component Analysis

Analyzing the above indicators alone is not sufficient to study and estimate the evolution of the thermal environment. Therefore, it is important to integrate information related to environmental parameters. For this purpose, PCA was conducted to measure the weight of the coefficient before establishing the Thermal Environment Index as a new environmental indicator [47]. In this process, the weight of each indicator is not manually determined; rather, it is automatically and objectively defined based on the contribution of the main component to its variance, which serves as the weighting factor for each principal component. This helps to avoid bias during the calculation process due to different weighting settings. Additionally, weights can be determined without prior knowledge of how these variables are related to environmental pressures [27]. The first principal component (PC1) contains the highest proportion of eigenvalues, with contribution rates of 58%, 60%, and 61% for the years 2000, 2013, and 2022, respectively, indicating that it integrates most of the characteristics of all the parameters. The eigenvalues for SAVI (greenness) and moisture in PC1 are positive, but the greenness value is greater than the moisture value, indicating that they have positive effects on the TEI, whereas the eigenvalues for LST (temperature), NDBI (urbanization), and NDSI (dryness) in PC1 are negative. The highest eigenvalue is obtained for urbanization, followed by temperature and then dryness, indicating that urbanization, temperature, and dryness have negative effects on the TEI (Figure 8).

6.7. Thermal Environment Index (TEI)

After analyzing the five environmental indicators and conducting a principal component analysis for each of these indicators, the Thermal Environment Index (TEI) was created. The TEI values range from 0 to 1 and are categorized from excellent to poor. The findings from 2000, 2013, and 2022 indicated that areas with poor environmental conditions were primarily concentrated in urban areas. Conversely, areas with excellent and good environmental conditions were situated outside of the urban areas, particularly in the northern and western regions of Riyadh city. This is illustrated in Figure 9.

Through an analysis of the data for the years 2022, 2013, and 2000 in Table 4, four classifications were used to assess the urban environmental condition as excellent, good, moderate, or poor following previous research [27], and the results are shown in Table 4.

It was found that the percentage of areas with good environmental conditions was the highest in the year 2000, with a total area of 3066 km², reaching 51% of the city's total area, while in the year 2013, it decreased by 456 km² to 2610 km², and continued to decrease in the year 2022 to 2301 km², reaching only 39% of the city's total area. Similar results were obtained for areas with excellent environmental conditions, with a percentage of 23% in the year 2000, which decreased to 17% in the year 2013 and then increased by 5% in 2022 to 22%. The main reason for the increase in the percentage of green areas in Riyadh is the Riyadh Green Project, which is one of the major projects contributing to achieving the goals of Saudi Vision 2030 [14].

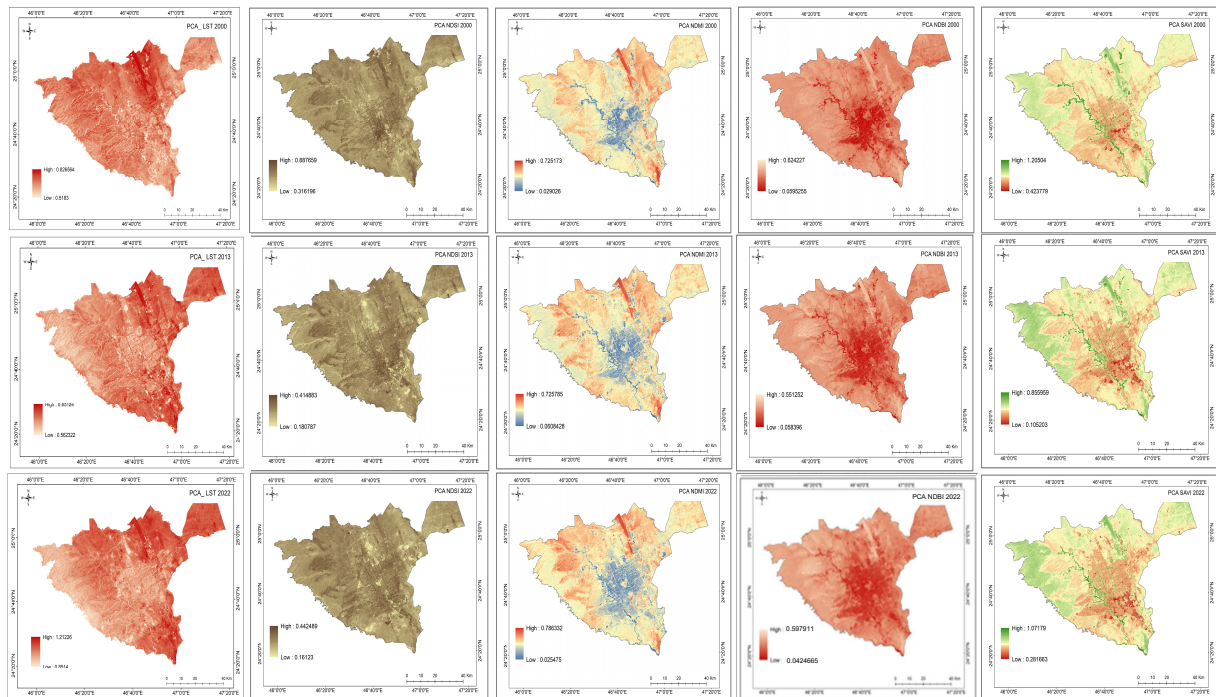


Figure 8. Principal component analysis.

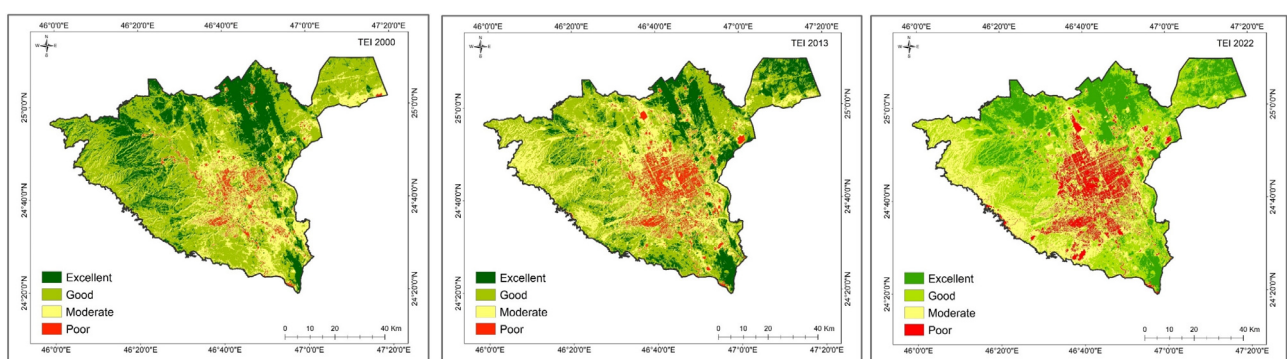


Figure 9. Thermal Environment Index.

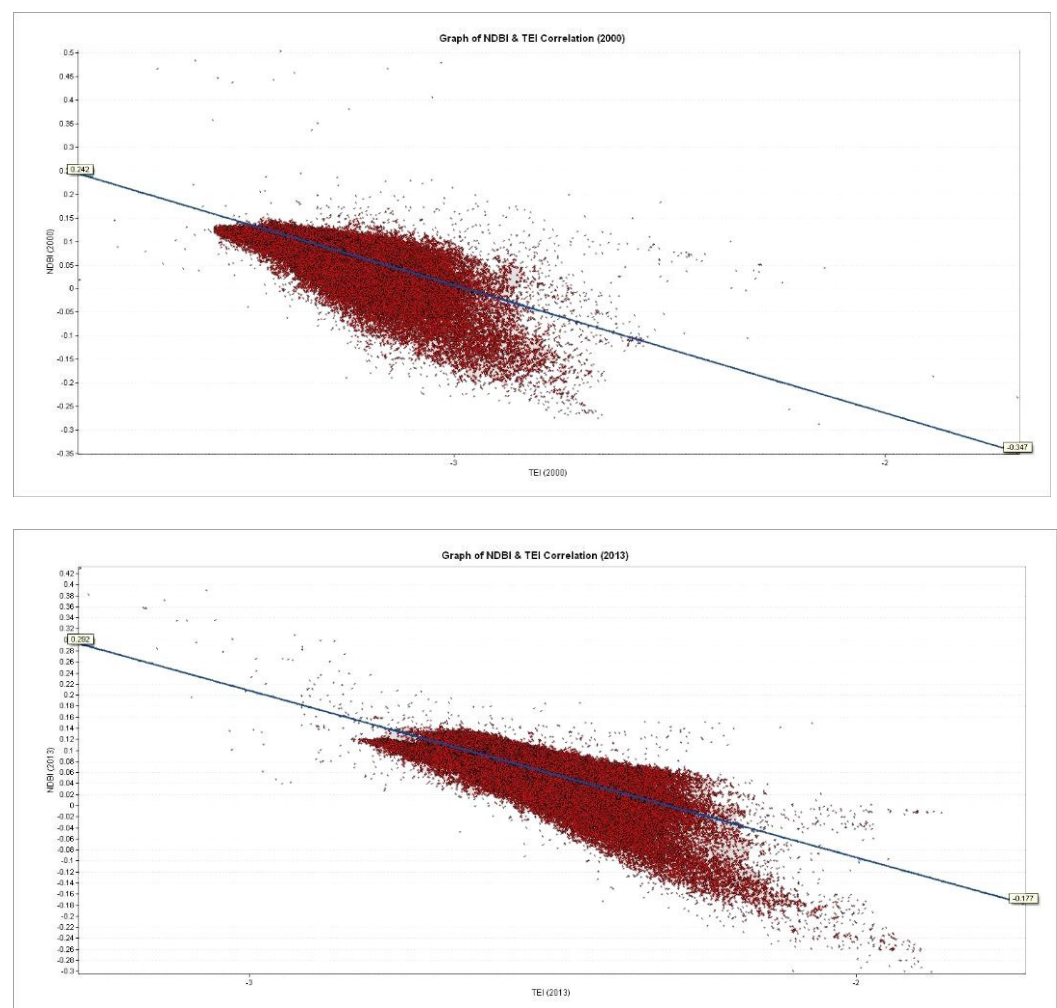
In contrast, the areas with poor environmental conditions increased, as they constituted 4% of the total area, equivalent to 240 km², in the year 2000, and increased in 2013 to 511 km² and in 2022 to 658 km². Based on the analysis of previous indicators, it is clear that urban sprawl negatively impacts the urban environment by reducing vegetation cover and increasing temperatures and other climatic elements. The index results of this study agree with the results of previous relevant studies on the impact of urban sprawl on the urban environment, such as [27], demonstrating that there is a negative impact of urban sprawl on urban environmental conditions.

Table 4. Thermal Environmental Index statistics.

TEI	Riyadh Area	2000		2013		2022	
		KM ²	Percentage	KM ²	Percentage	KM ²	Percentage
Excellent	5962	1345	23%	995	17%	1327	22%
Good	5962	3066	51%	2610	44%	2301	39%
Moderate	5962	1307	22%	1844	31%	1673	28%
Poor	5962	240	4%	511	9%	658	11%

6.8. The Relationship between Urban Sprawl and Urban Environmental Conditions

The linear relationship between urban sprawl and the Thermal Environment Index was assessed using GIS techniques. The result showed an inverse relationship, wherein increased urban sprawl corresponded to weaker or lower urban environmental values, as shown in Figure 10. To measure the strength and direction of the linear relationship between urban sprawl and poor environmental conditions, Pearson's correlation analysis was performed. It was found that the relationship between the two variables, urban sprawl and poor environmental conditions, resulting from several indicators combined with the Thermal Environment Index, shows a very strong correlation, reaching a value of 0.9. This means that an increase in urban areas results in more areas with weak environmental conditions.

**Figure 10.** Cont.

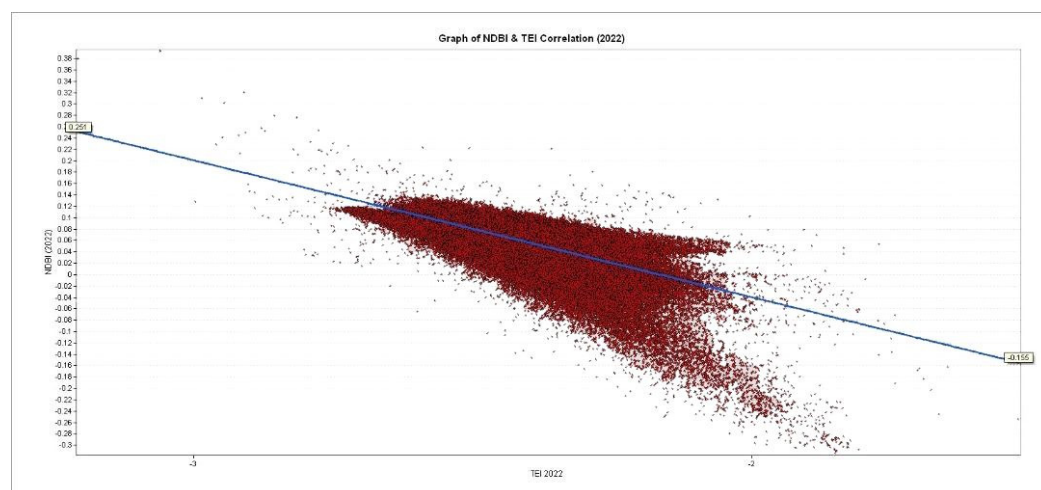


Figure 10. Linear relationship between urban sprawl and the Thermal Environmental Index.

An increase in urban areas leads to poor environmental conditions due to various factors. Urban sprawl causes the conversion of natural landscapes into built-up areas, leading to the loss of vegetation like forests and wetlands. This loss reduces the ecosystem's ability to regulate temperature, sequester carbon dioxide, and support biodiversity. Additionally, urban expansion results in the proliferation of impervious surfaces, hindering water infiltration into the soil and causing issues like reduced groundwater recharge and increased surface runoff. The urban heat island effect is exacerbated by urban sprawl, raising temperatures and compromising air quality. Urban sprawl also fragments natural habitats, limiting species' movement and access to resources, further degrading ecosystem functioning. These factors collectively contribute to the correlation between urban sprawl and poor environmental conditions, including degraded natural ecosystems, increased impervious surfaces, and an exacerbated urban heat island effect.

7. Discussion

When applying the newly established Thermal Environmental Index (TEI), which includes several indicators (urban built environment, vegetation cover, temperature, and levels of dryness and moisture), to evaluate urban environmental conditions during 2022, 2013, and 2000 and reclassifying them into “excellent”, “good”, “moderate”, and “poor” categories, as in [27], it became evident that the label of “good” environmental conditions applied to the highest percentage of urban areas, as well as areas outside the city, during the time periods. In 2000, areas with “good” environmental conditions represented 51% of urban areas, and this number decreased to 39% in 2022, indicating a deterioration of the urban environment. Upon investigation, the causes behind this deterioration were found to be uncontrolled urban expansion and population density increase, as confirmed by [48], which indicated that urban expansion puts significant pressure on resources and other vital components, thus negatively affecting the ecosystems surrounding urban settlements.

Regarding the areas with “excellent” environmental conditions, distributed outside the city, they witnessed a slight increase of 5% in 2022 compared to 2013. This increase can be attributed to the Green Riyadh Project, which aimed to increase green areas and improve air quality and urban life, as confirmed by the research conducted in [8], which mentioned this improvement in urban center quality as an indicator of urban design efficiency and effectiveness. In contrast, areas classified as having “poor” environmental conditions witnessed a continuous increase during the time periods studied, from 4% of the total urban areas in 2000 to 11% in 2022. This increase may be attributed to urban expansion and population increase, leading to the depletion of natural resources and environmental deterioration in some areas due to the transformation of natural lands into residential or industrial areas, as confirmed by [27], in which urban expansion was associated with a

deterioration in vegetation cover and a loss of biodiversity, which also affected the air and water quality in the region.

Pearson's correlation analysis showed that the relationship between the two variables—urban sprawl and poor environmental conditions resulting from several indicators combined with the Thermal Environment Index—shows a very strong correlation, reaching a value of 0.9, as confirmed by [27], according to which environmental degradation can result from urban expansion. Therefore, implementing a city development plan and rational city management steps is necessary to mitigate this impact.

Using the correlation coefficient, the relationship between the studied environmental indicators and the Environmental Heat Index was examined, aiming to estimate the influence of each indicator on the Environmental Heat Index and identify its contribution towards developing future solutions. This study revealed a positive relationship between vegetation cover and humidity, while the relationship was negative with respect to temperature and drought. Based on these results, it was found that vegetation cover represents the primary influence on environmental indicators, as well as playing a crucial role in regulating moisture levels and reducing drought in the environment, according to the Environmental Heat Index [49]. It also contributes to climate improvement by cooling the environment and mitigating heat variations. The Green Riyadh Project took several measures to improve urban environmental quality and mitigate the effects of climate change, achieving notable results such as a decrease in air temperature in the city of 1.5–2 degrees Celsius and improved air quality, obtained by increasing air humidity [14]. This is confirmed by the current study, which showed excellent environmental improvements in 2022 compared to 2013, aligning with the goals of Saudi Vision 2030 in the Green Riyadh project, aiming to increase vegetation cover by 541 km², with expectations of environmental improvement in the future [14]. This underscores the importance of plants in mitigating the impacts of urban expansion on the urban environment, which contributes to alleviating the negative effects on the urban environment and improving the quality of life for the residents [50]. It is urgent to accurately quantify the relative contribution of urbanization and meteorological changes to better understand the driving mechanisms of urban vegetation change, especially considering the significant impact of environmental factors such as air temperature and urban heat islands on urban vegetation globally [51].

8. Conclusions

The results of this study provide insights into the urban environmental conditions in Riyadh over time. The index developed using principal component analysis, as the Thermal Environment Index (TEI), incorporates several indicators to assess urban environmental conditions. The findings indicate a pattern of distribution of environmental conditions during the study period, with urban areas predominantly having poor and moderate environmental conditions and areas outside the city having excellent and good environmental conditions, particularly in the northern and western parts of Riyadh. Pearson's correlation analysis demonstrated a strong correlation (0.9) between urban sprawl and poor environmental conditions. This indicates that, as urban areas expand, the prevalence of areas with poor environmental conditions increases.

9. Recommendations

Based on the findings of this study, the following recommendations are proposed:

- Continuous Review and Monitoring: It is essential to establish a system for the continuous review and monitoring of the urban environment in Riyadh using geospatial techniques. Regular assessments will enable the identification of areas experiencing deteriorating environmental conditions and facilitate timely interventions.
- Comprehensive Research Initiatives: Similar research initiatives should be conducted to assess the urban environment using various indicators, including those related to environmental pollution. This comprehensive approach will provide a more holis-

tic understanding of the environmental challenges faced by the city and aid in the formulation of effective strategies.

- Achieving Balance in Urban Expansion: Efforts should be directed towards achieving a balance in the urban expansion process. This can be achieved through the implementation of appropriate environmental regulations and controls alongside urban development. Sustainable urban planning practices, such as incorporating green infrastructure and efficient resource management, should be prioritized to reduce pressure on environmental resources.

By implementing these recommendations, Riyadh can strive for a more sustainable and environmentally friendly urban environment. The findings and insights from this study can serve as a foundation for future initiatives aimed at improving the quality of the urban environment and promoting sustainable development not only in Riyadh but also in similar regions around the world.

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