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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: This study examined the impact of urban expansion on the urban environment in Riyadh city, which is one of the key areas of interest for the international community in general and the Kingdom of Saudi Arabia in particular. Achieving environmental sustainability is among the goals of Saudi Vision 2030. Riyadh has recently witnessed urban expansion due to population growth, which poses 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 (the 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 55% compared to in 2000. The results also show that, in 2000, 2013, and 2022, areas of poor and weak 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 with weak 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 obtain livable cities that are more sustainable in the long run [3]. The increasing demand for urban spaces and the significant increase in population contribute 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 involves 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, as well as increasing pollution rates and traffic congestion along with physical and psychological illnesses [5]. The environment is the most affected element as the impact of urban sprawl negatively affects ecological services, which refer to the benefits that humans derive from the environment such as energy, water, and other resources [6]. In terms of increasing demand for resources, rising greenhouse gas 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 [7].

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 [8]. Urban sprawl in most Saudi cities has contributed to many environmental problems, such as pollution and depletion of natural resources [9]. 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 [10]. Riyadh is one of the most important Saudi cities that has witnessed tremendous growth as its population increased, and its urban areas have expanded significantly with substantial urban sprawl towards its outskirts and surrounding cities [11]. The rate of urban sprawl reached 82.9% between 1987 and 2017 [12]. Consequently, the steady population and urban growth has led to population congestion in certain areas, which threatens to increase negative environmental impacts unless this growth is accompanied by the development of appropriate environmental regulations and controls [13].

This study aims to assess the impact of urban expansion on the urban environment in Riyadh from 2000 to 2022. This will be achieved by introducing an index, the Thermal Environmental Index (TEI), to measure and evaluate the current situation and propose solutions to address and prevent environmental problems. These solutions will also contribute to understanding the nature of urban expansion in the study area, its implications on urban environmental components, and impact on the environment.

2.1. Impact of Urban Sprawl on Vegetation Index

Urban sprawl primarily affects agricultural lands, as expansion usually occurs at the expense of these lands. When examining and interpreting the impact of urban sprawl on the vegetation index or vegetation cover, the authors of [11] reached a similar conclusion to the authors of [7,14] in terms of a decline in natural vegetation as a result of urban sprawl. However, the authors of [7] excluded city centers from their analysis, and these studies differed in their scope of application and the methods used to examine the impact of urban sprawl. In [11], which analyzed the impact of urban sprawl on agricultural lands in Riyadh using a historical, descriptive, and spatial analysis involving quantitative and qualitative research methods, including distributing a questionnaire to a randomly selected sample of 272 residents of the area and conducting field interviews with specialists and agricultural land owners, the results showed that urban sprawl has an impact on open natural spaces and contributes to a decline in agricultural lands. In contrast, [7], which examined the impact of urban sprawl on vegetation cover in China during the first eighteen years of the twenty-first century, relied on changes in urban areas and differences in natural vegetation cover (Normalized Difference Vegetation Index, NDVI) in China's urban areas from 2000 to 2018 to examine the impact of expansion on vegetation cover. This study showed a high degree of difference in the vegetation cover index, with a high deterioration of vegetation cover in urban areas. However, city centers witnessed an improvement in the level of vegetation cover due to efforts focused on increasing green spaces in urban areas as an indicator of the efficiency and effectiveness of urban design.

The author of [14] examined the impact of urban sprawl in Mankato, USA, on the local environment using both a descriptive historical approach and an analytical approach, where photographic images were processed by means of high-precision remote sensing techniques. This study concluded that urban sprawl led to an increase of 14.3% in the percentage of impervious surfaces in urban areas, covering a similar percentage of land as that (15.1%) of agricultural and

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grassy lands in Mankato. The study also demonstrated the impact on local surface runoff and water quality. These findings provide policymakers with a timeline and spatial location for changes in the natural landscape and the potential environmental and economic impacts that may result from urban sprawl.

However, the findings of [15] affirmed the results of [7], as the study showed that the impact of urban sprawl is not clear and varies greatly from region to region. The authors reached this conclusion by using a Land Change Modeler (LCM)–Markov Chain model and determining its coefficients on the observed changes between 1988/1989 and 1999 and verifying them with the observed urban form for 2014. This study also used models to simulate urban expansion by 2030 and then compared land uses in 2030 with the baseline plan. Th study results indicated that there are large differences in the expected spatial structure for 2030 and planned development in terms of density, distance, shape, and spatial pattern. The study results also showed that spatial pattern is greatly affected by rapid urban expansion and planning policies.

With regard to the direction of urban sprawl on agricultural lands, the results of [16], which was conducted in Al-Ahsa, Saudi Arabia, are similar to the results of [17], showing that the agricultural lands most affected by urban sprawl are those located near the main roads. The authors of [16] indicated that using remote sensing technologies helps identify the direction of urban expansion. Their study also showed that geographic information systems and remote sensing technologies can help planners make design decisions to protect agricultural lands while taking into account the natural and social characteristics of the province and its inhabitants.

These findings were reached by utilizing descriptive and field methods, in addition to the historical method. The necessary information was obtained by reviewing relevant studies, books, and other publications; conducting field visits; and examining statistics, maps, and aerial photographs. To achieve the study objectives, the authors used statistical analysis software (SPSS), remote sensing technologies, and the ER Mapper system to process and analyze satellite imagery data, as well as converting satellite imagery data into digital image files.

The findings of [17], which was conducted in the Palestinian cities of Ramallah and Al-Bireh, showed that Israeli occupation contributed significantly to the urban situation of these two cities, as it worked to identify the growth directions and provided facilities in certain areas while preventing such facilities in others. In addition, population growth in these two cities increased due to the occupation practices and conditions occurring in Palestine since 1948.

This study also showed that the population increase and expansion in these two cities led to increased burdens on municipalities and responsible authorities, as well as contributing to exacerbating the traffic congestion crisis. These results were reached by utilizing historical and descriptive methods, including conducting interviews and examining aerial photographs to interpret the pattern of urban expansion and direction through the use of geographic information systems and remote sensing software.

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 [18]. When discussing the impact of urban sprawl on the moisture index, the conclusion of [19] is similar to that of [20] regarding the impact of urban sprawl on the moisture index. The results of [19] showed that the 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 the 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 [20], 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 [21–23] are consistent in terms of the impact of urban sprawl on soil and its components. The authors of [21] 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 [22]. 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 [23], 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 [24] are similar to the findings of [25]. The findings of [24] 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, [25] 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, in 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 [26], 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 [27] 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 became better 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 [28] 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 city. 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 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 Malah et al. (2021) and Niu and Li (2020), focused on assessing urban environmental quality using an environmental quality index without considering urban expansion. Meanwhile, other studies, like those conducted by Indrawati et al. (2020), primarily focused on evaluating urban environments using an integrated environmental index consisting of four indicators (greenness, moisture, drought, and cumulative clustering). The study by Zhu et al. (2019) 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

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Riyadh is the capital of Saudi Arabia, which is located at latitudes (24°23′07″ 25°0′20″N) and longitudes (46°27′57″ - 46°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 [29]. 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.

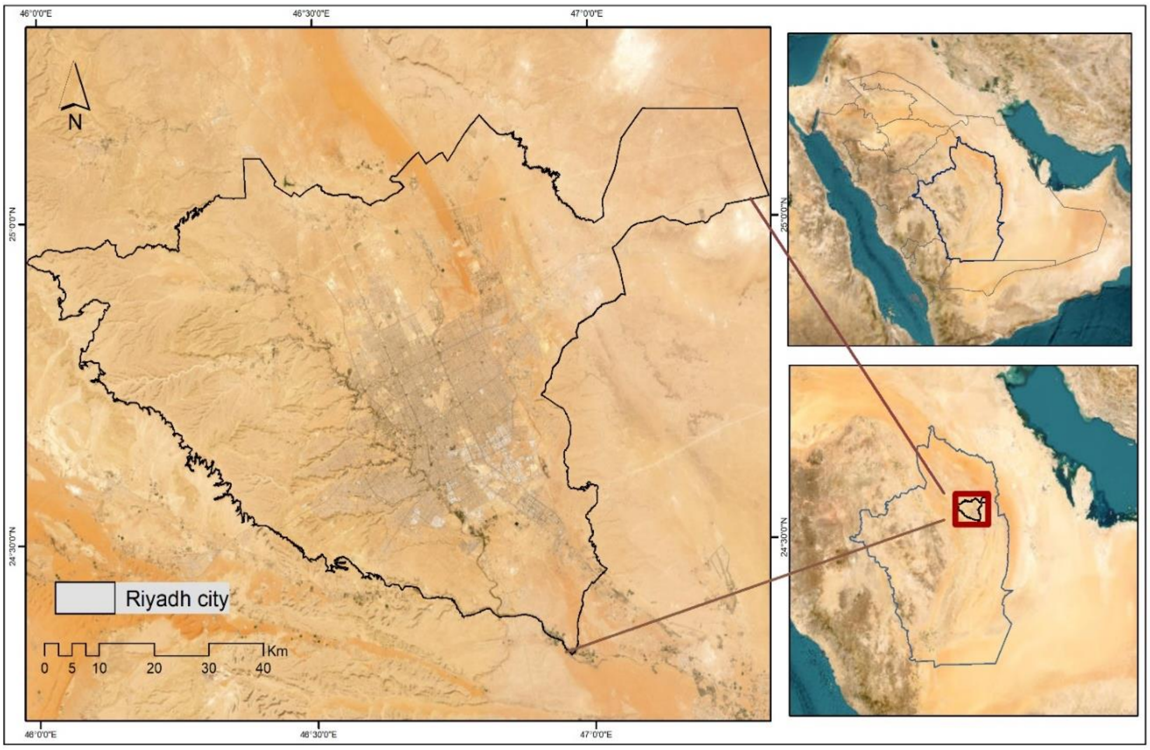

Figure 1. Study area.

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 USGS Landsat satellite missions, which is a series of satellite missions launched by the National Aeronautics and Space Administration (NASA) and the US Geological Survey, aiming to monitor the Earth and collect data and images for research on global changes in agriculture, urbanization, and other applications [30]. Satellite imagery data for the year 2000 were obtained from the Landsat-5 satellite, which is a satellite launched by NASA in 1984 to collect images of the Earth's surface. It takes about 16 days to completely scan the Earth and reaches an altitude of 705 km with a polar sun-synchronous orbit and an inclination angle of 98.2, and the spatial coverage is 185 km.

The Landsat-5 satellite contains two sensing systems.

The first is a Thematic Map (TM) sensor, which records radiation in seven spectral bands, three of which are within the visible rays (3, 2, and 1), while the remaining spectral bands (7, 6, 5, and 4)

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are within the infrared rays (near, short, thermal, and reflected). This sensor is characterized by a spatial resolution of 30 m for all bands, except for band 6, which has a resolution of 120 m.

The second system is a Multispectral Scanner (MSS) sensor, which records radiation in four spectral bands, that is, two bands (5 and 4) within the visible rays and two bands (7 and 6) within the near-infrared rays, with a spatial resolution of 80 m.

Additionally, satellite imagery data for the years 2013 and 2022 were obtained from the Landsat-8 satellite, which was launched in February 2013 and scans the entire Earth every 16 days. New sensors were added to this satellite, including an Operational Land Imager (OLI) and a Thermal Infrared Sensor (TIRS) containing 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 from the month of August. Then, the data were processed to prepare them for analyses using geographic information system software; 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 [31] and their relationship to urban sprawl. It used an experimental method to identify the causal relationship between variables [32], 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.

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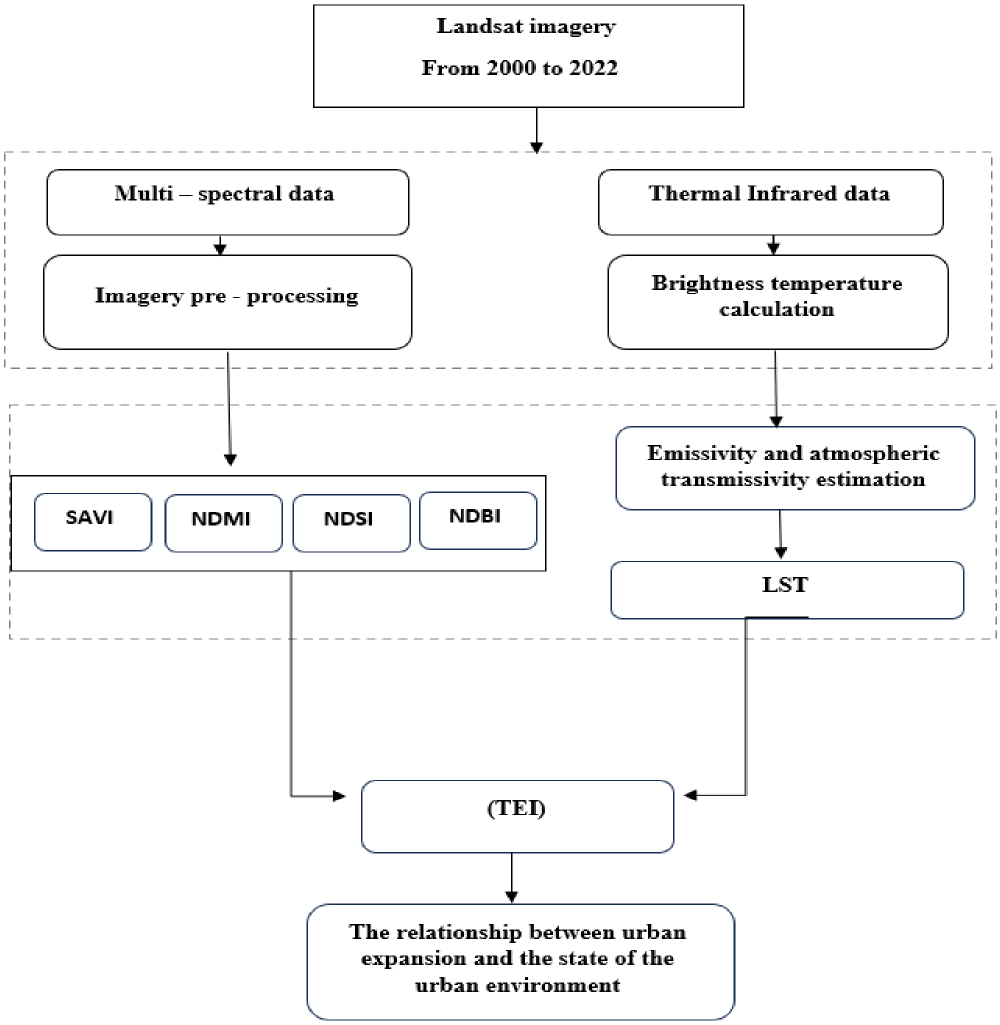

Figure 2. Study methodology.

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 [26,33] assessed the state of 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	$NDBI = (\mathrm{SWIR1} - NIR)/(\mathrm{SWIR1} + \mathrm{NIR})$	[34]
SAVI	$SAVI = (\mathrm{NIR} - RED)/(\mathrm{NIR} + \mathrm{RED} + \mathrm{L})\ (1 + L)$, $where\ L = 0{,}5$	[35]
NDMI	$NDMI = (NIR - SWIR2)/(\mathrm{NIR} + \mathrm{SWIR2})$	[26]
NDSI	$NDSI = (BSI + NDISI)/2$ $BSI = (SWIR1 + RED - BLUE - NER)/(\mathrm{SWIR} + \mathrm{RED} + \mathrm{BLUE\_NIR})$ $MNDWI = (GREEN - SWIR1)/(\mathrm{GREEN} + \mathrm{SWIR1})$ $NDISI = (TIR - MNDWI + NIR + SWIR1/3)/(TIR + MNDWI + NIR + SWIR1/3)$	[26]
LST	Derivation of spectral: Ly = ML * Qcal + AL – Qi	[36]

radiation based on TOA radiation	
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 = Square(NDVI - NDVImin) / (NDVImax - NDVImin)
Spectral emissivity values	E = 0.004 * Pv + 0.986
Temperature	LST = (BT / (1+ (0.00115 * BT / 1.4388) * ln(E)))
Convert temperature into an index	$T=\sqrt{\frac{C}{10}}+0.1$

5.3. Constructing the Thermal Environment Index (TEI)

A principal component analysis (PCA) was used based on [26,33] to construct the TEI as follows:

TEI=1−Σai(PC)i

where Σai(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) [37].

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 km2	24 km2	18 km2
Area with less vegetation density	89 km2	79 km2	86 km2

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 meters, 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 meters, 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 exploited this natural resource, which led to its deterioration. Such practices included logging, overgrazing, and urban sprawl [38]. 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 [13].

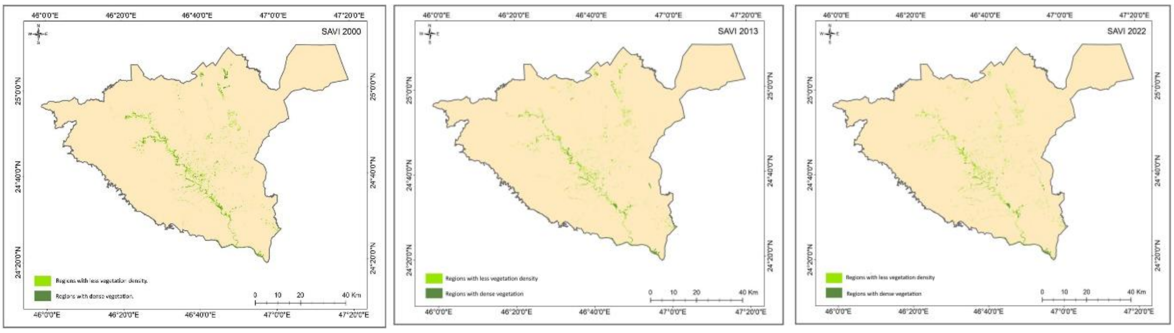

Figure 3. Vegetation cover index in 2000, 2013, and 2022.

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 city in the years 2022, 2013, and 2000. The urban clustering area in the year 2000 was about 442 km2, while in the year 2013, the area was about 760 km2. In the year 2022, the urban clustering area increased to 988 km2, showing an increase of about 228 km2 compared to the previous time period at a growth rate of 24% (Figure 4).

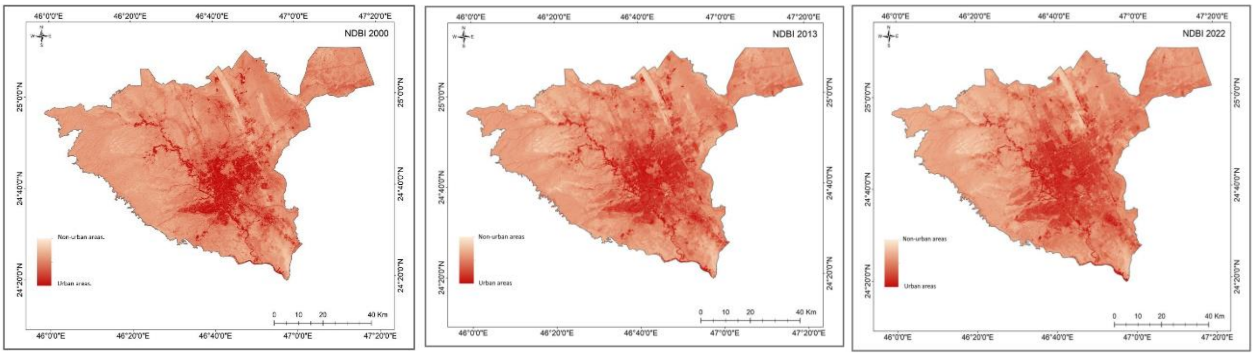

Figure 4. Urban index in 2000, 2013, and 2022.

The reason behind this urban sprawl is likely due to the increasing population, which is largely caused by high fertility and internal and external migration rates. The results of [39,40] 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	717381
2010	5,254,560	857764
2022	7,009,120	2,426,816

6.3. Moisture Index (NDMI)

The NDMI is a moisture index that reflects the moisture content in soil and vegetation cover [41]. 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.

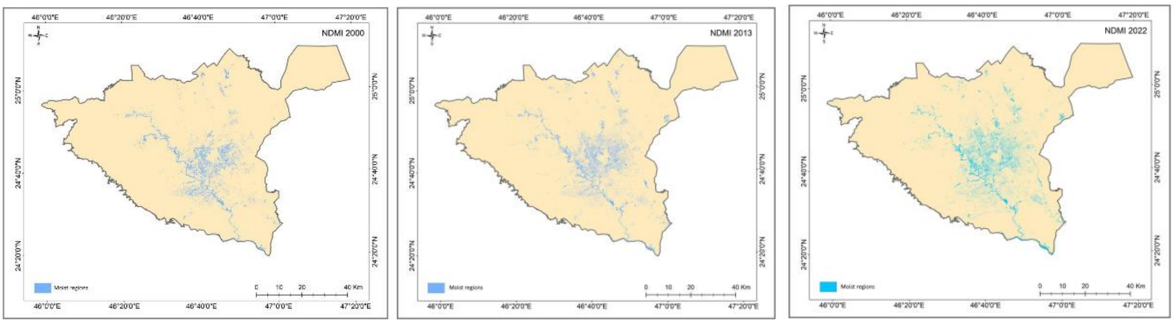

Figure 5. Moisture index in 2000, 2013, and 2022.

6.4. Dry Index (NDSI)

The dry index was used to identify exposed bare soil. It was calculated by taking into account the NDISI to identify the distribution of bare land, as this index determines the degree of dryness [42].

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 [43]. Accordingly, we found that the dry areas are generally distributed in the city and concentrated in residential areas.

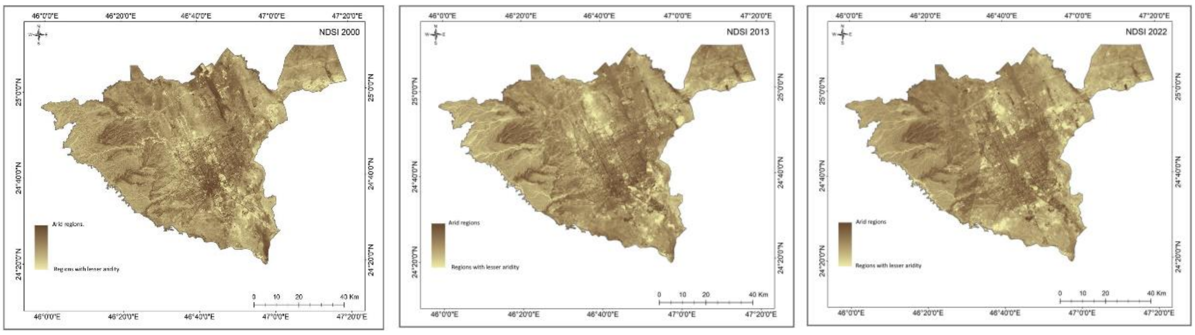

Figure 6. Dry index in 2000, 2023, and 2022.

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 [44].

The LST index was used to extract surface temperatures during the summer seasons. 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 [45].

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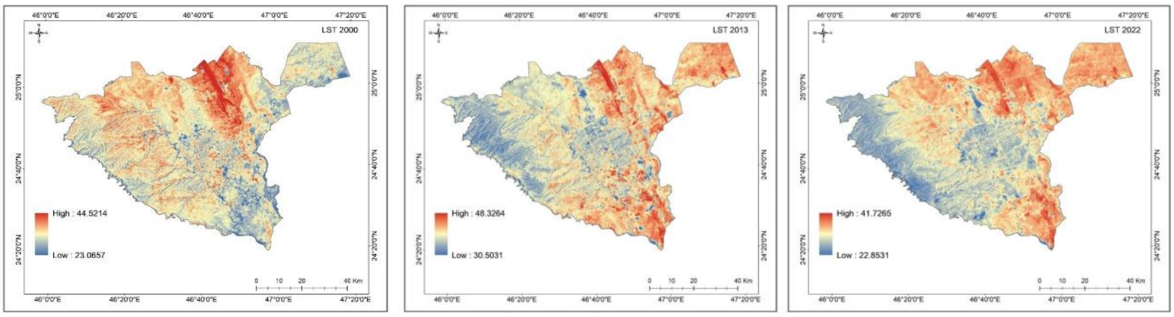

Figure 7. Land surface temperature index in 2000, 2013, and 2022.

6.7. 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 [46]. 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 [26]. 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.

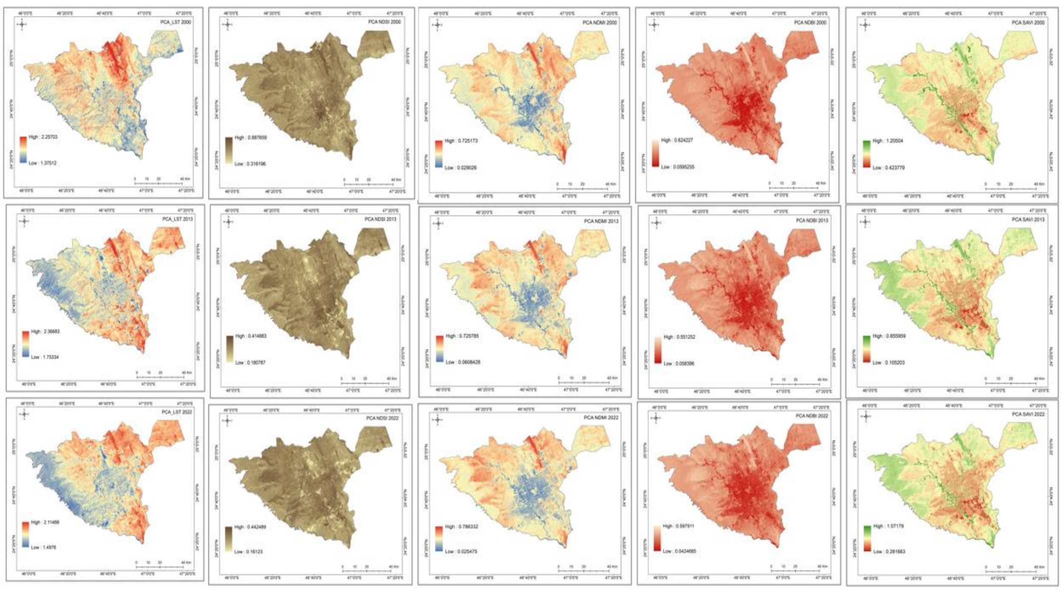

Figure 8. Principal component analysis.

6.8. Thermal Environment Index (TEI)

After completing the analysis of the five environmental indicators (urban index, vegetation cover index, moisture index, dry index, and temperature index) and performing the principal component analysis using each of these indicators, the Thermal Environment Index (TEI) was constructed, which is an index that evaluates and accurately predicts the urban environmental conditions. The values range from 0 to 1 and are classified from excellent to poor. The results in the years 2000, 2013, and 2022 showed that the areas of poor and weak environmental conditions were distributed mainly in urban areas, whereas areas with excellent and good environmental conditions were located outside of the urban areas towards the northern and western parts of Riyadh city, as shown in Figure 9.

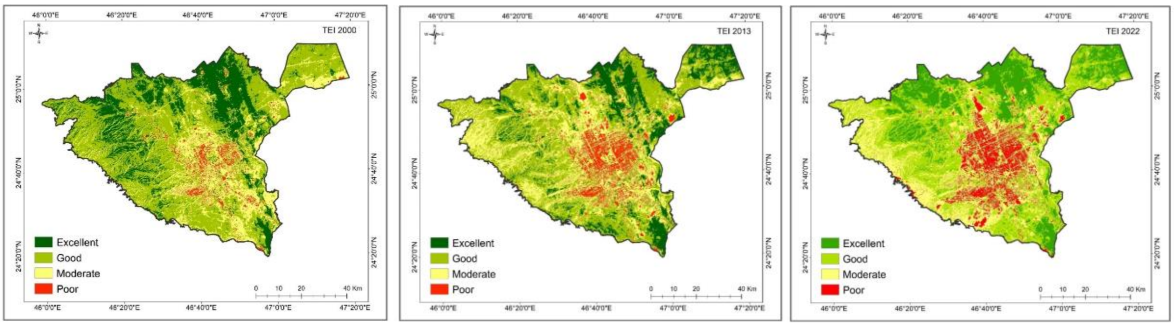

Figure 9. Thermal Environment Index in 2000.

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 [26], 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 [13].

Table 4. Thermal Environmental Index statistics.

TEI	Riyadh Area	2000 in km2	2000 in %	2013 in km2	2013 in %	2022 in km2	2022 in %
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%**

In contrast, the areas with weak 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. 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 [26], demonstrating that there is a negative impact of urban sprawl on urban environmental conditions.

6.9. 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 weak environmental conditions, Pearson's correlation analysis was performed. It was found that the relationship between

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the two variables urban sprawl and weak 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.

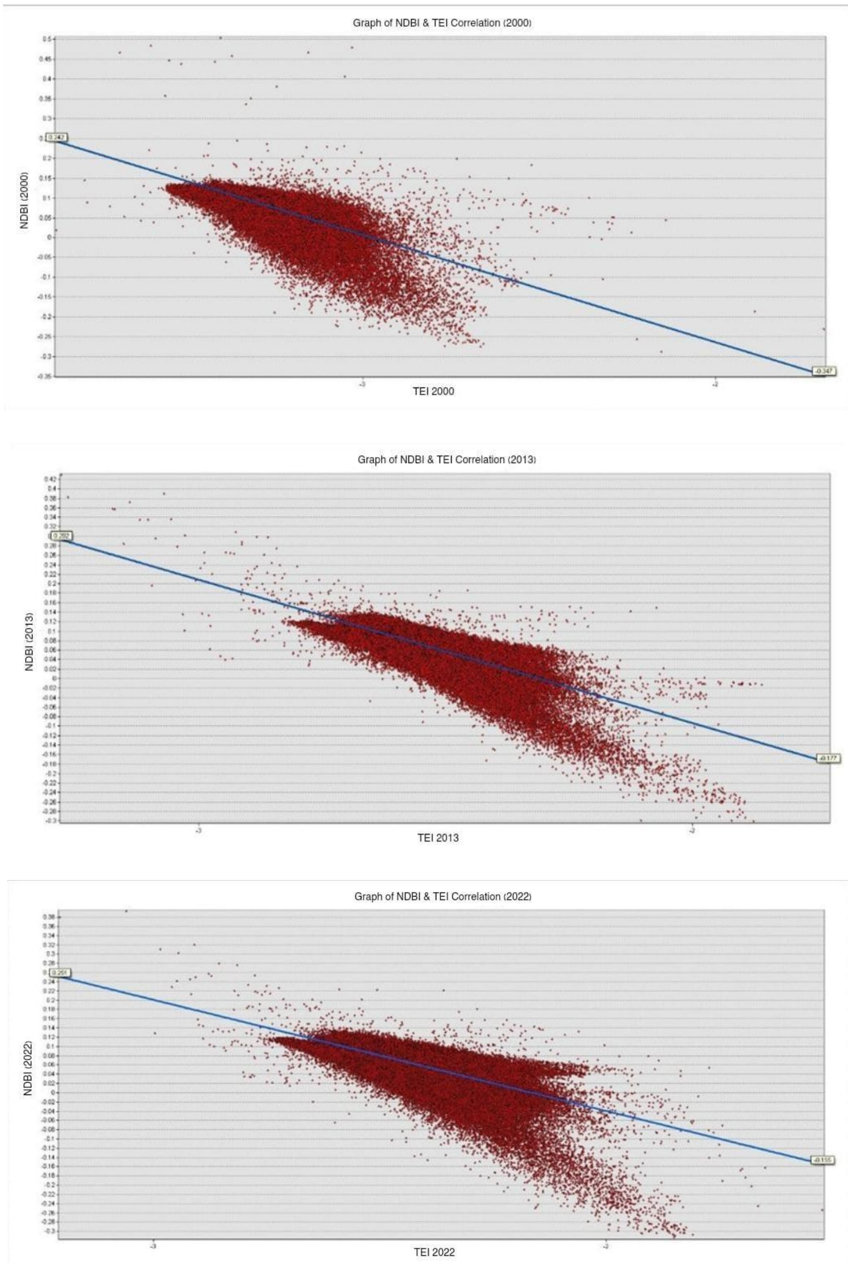

Figure 10. Linear relationship between urban sprawl and the Thermal Environmental Index.

An increase in urban areas leads to weaker 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 weaker 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 [26], 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 the 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 [47], 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 [7], 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 [26] 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.

The Pearson's correlation analysis showed that the relationship between the two variables—urban sprawl and weak 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 [26], 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 [48]. 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 [13]. 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 km^2, with expectations of environmental improvement in the future [13]. 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 [49].

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, known 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 weak environmental conditions. This indicates that, as urban areas expand, the prevalence of areas with weak 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 holistic 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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