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RESEARCH ARTICLE

# Analysis of Urban Heat Island Effects in the City of Annaba, Algeria: The Role of Green Structures and GIS and GEE Remote Sensing Technologies

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**ABSTRACT**

Climate change is a crucial factor in developing and managing urban and suburban areas, necessitating careful consideration in urban planning and management. The intensification of extreme weather events, such as heat waves, coupled with the urban heat island effect and rising global temperatures, renders cities and their populations exceptionally vulnerable. Annaba, Algeria's fourth-largest city, has experienced rapid urbanisation in recent decades, significantly reducing green spaces. Ongoing pressure from housing and facility construction, as well as densification, further exacerbates this trend, compromising environmental performance and sustainability. This study employs remote sensing techniques using the Google Earth Engine (GEE ) platform and Geographic Information System (GIS) via QGIS to analyse the correlation between Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI), with a focus on the value of green structures. The correlation between land use, vegetation cover, and surface temperature has significant environmental implications. The study area and selected samples exhibited variations in soil surface temperature, indicating differences in maximum surface temperatures for 1984, 2004, and 2021. An increase in surface temperatures in urban areas was observed, confirming the negative impact of urbanisation on Annaba's environment. Current planning practices do not adequately account for green structures, which are essential for maintaining cooler temperatures.

## 1. INTRODUCTION

By 2030, the majority of the world's population growth is expected to take place in cities, particularly in developing countries. According to United Nations projections, urban growth offers attractive opportunities but also generates negative social, political, economic and environmental impacts. Managing this problem will remain challenging for many developing countries [1]. The uncontrolled expansion of urbanisation has made territories vulnerable to the risks of climate change. Urgent measures must be taken to significantly reduce greenhouse gas emissions over the coming decades [2],[3].

Urbanisation contributes significantly to changes in land use and cover, making it a crucial factor to consider in the context of climate change. In addition, the Mediterranean region is particularly vulnerable to climate change and has been identified as a 'hot spot' for its effects [4]. The well-known effects of climate change include the already high concentration of $CO_2$, which has risen from 280 to

415 ppm since 1880. Emissions of CO2 and other greenhouse gases are expected to increase the average temperature by 1 to 4°C over the next century [5]. In addition, the frequency and intensity of extreme weather events will increase, particularly droughts, which are defined as an unusual and severe lack of water [6].

The United Nations Environment Programme (UNEP) implemented the GLASOD programme (Global Assessment of Human-induced Soil Degradation) in 1991, with the support of the World Soil Organisation and World Soil Information (ISRIC). The programme published a map describing the state of soil degradation worldwide caused by human activities. One potential risk associated with these changes is that the flora may not be able to adapt to the rapid fluctuations in its immediate ecosystem [7]. This could result in degradation or even a decline in plant cover. The reduction in greenery, especially in densely populated areas where temperatures tend to be higher, is responsible for this effect [8]. Urban planning and development face a significant challenge in addressing these risks.

The Mediterranean city of Annaba has undergone rapid urbanisation in recent decades. This has led to changes in land cover and land use, resulting in high land consumption, particularly of green areas such as forests, agricultural land and green spaces [9]. The trend towards degradation of soils and ecosystems, as well as the increase in local temperatures, is continuing due to the massive pressure exerted by the production and densification of housing and facilities. It is essential to analyse the role of green structures in regulating ground surface temperatures, especially in the context of climate change and urban heat islands.

Annaba now includes surrounding urban areas such as Sidi Amar, El-Hadjar El Bouni, and Draa Erich. This urban expansion has negatively impacted agricultural land and led to a chaotic fragmentation of the urban fabric. The relationship between the city and its territory is problematic and challenging to manage [10].

The supply of building land in the city has not been able to keep pace with the increase in demand, leading to saturation and the encroachment of forests and agricultural areas in a state of anarchy. There are many reasons for this, but in the age of sustainable development, the environment and quality of life are now central concerns. This is due, in particular, to the growing awareness of ecological issues, which are at the forefront of all international policies.

Changes in land occupation and use often lead to a retreat or Fragmentation of the green structure [09], which has a negative impact on the environmental performance and sustainability of the future [11]

Green structures are not considered in urban planning. Although they may be included in some development plans, they are not a priority for local authorities, especially when faced with other demands and needs of the population [12] . The expansion of built-up areas onto agricultural or wooded land persists, whereas urban expansion should have been encouraged in unproductive areas to preserve these resources. Similarly, clearing woodland areas for urban development disrupts biodiversity and undermines sustainability [13].

Remote sensing techniques and geographic information systems can be decision-making tools without reliable statistical and cartographic data. It is essential to consider the close relationship between land use and land cover (LULC) and surface temperature (LST) as an indicator when planning. The use of LULC and SST as indicators for planning is well-established in the literature. Weng al (2004) [14] and Voogt and Oke (2003)[15] both emphasise the importance of remotely sensed data, in particular the Normalised Difference Vegetation Index (NDVI), in identifying cooler areas with vegetation and their impact on surface temperatures.

These studies collectively demonstrate the value of land use and land cover (LULC) and land surface temperature (LST) data, in particular the normalised difference vegetation index (NDVI), for understanding and planning environmental change.

## 2. PRESENTATION OF STUDY AREA

### 2.1 Geographic situation

Annaba's geo-strategic position, natural potential, and diversified infrastructure make it a regionally influential province with potential international expansion. Annaba is the fourth largest wilaya in Algeria, following Algiers, Oran, and Constantine. It is situated in the extreme northeast of the country. It covers an area of 1439.20 km², representing 0.06% of the national territory. Geographically, Annaba is bounded by the Mediterranean Sea to the north with a distance of 80 km, the Wilaya of Guelma to the south, the Wilaya of El Taref to the east, and the Wilaya of Skikda to the west. Figure 1 presents its regional, national and even international importance.

The physical landscape of the area is diverse, encompassing plains, mountains, hills, and coastline. Most of this Mediterranean metropolis is situated on the plains, which comprise 18.08% of the territory, or 255 km². The Kherraza plain constitutes the majority of these plains. The northern part of the city is surrounded by the expansive green mountains of the Edough, which cover an area of 736 km². It also has a dense hydrographic network, including Lake Fetzara, a Ramsar site (freshwater) covering 18,670 ha, and the 127.5 km-long Oued Seybouse.

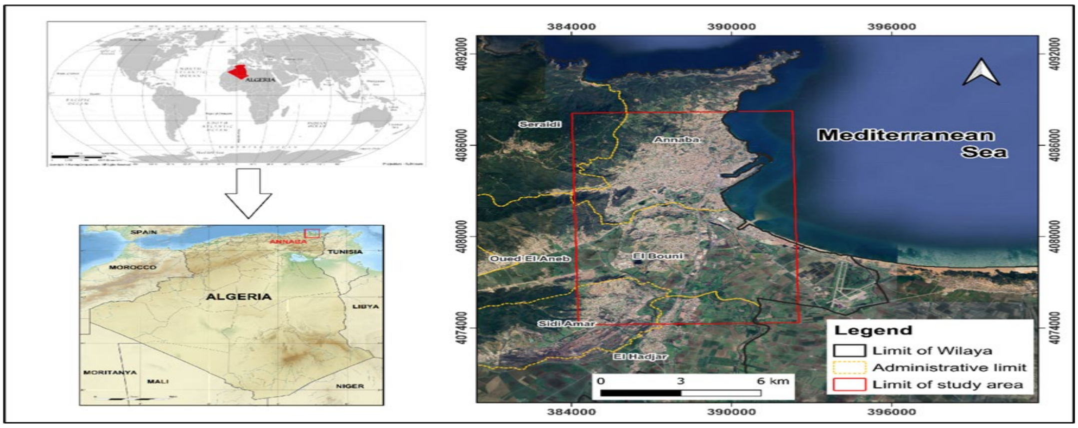


**Figure 1: The geographic situation of the study area**

### 1.2 Climatic condition

The study area has a sub-humid temperate climate, hot and rainy in winter and hot and humid in summer. The average maximum temperature of 32°C is recorded in August, while the average minimum temperature of 6.58°C is recorded in January.

Precipitation in Annaba is significantly higher in winter from October to Mai and very poor in summer from June to September. Figure 2 represents the annual rainfall evolution from 1982 to 2022, ranging from 550 to more than 900 mm.

Annaba's climate is influenced by its natural features, particularly Mount Edough, Lake Zara, and the Mediterranean Sea. Precipitation in the region comes mainly from the Edough mountains, which can produce rainfall of over 800 mm.

Water availability is crucial to plant development and diversity, with rainfall being the primary source. Climatic parameters such as potential evapotranspiration (PET) and relative humidity (RH) have significant agroecological impacts on plant growth [16] . In addition, water availability is the primary factor limiting vegetation growth and a crucial factor in determining its floristic composition in the Mediterranean region.

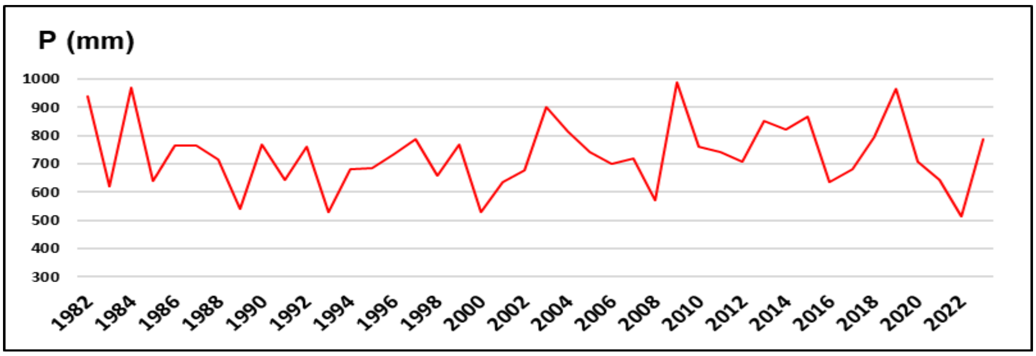

**Figure 2: Average rainfall variation over Annaba (Period: 1984 - 2021)**

Temperature is a critical environmental factor affecting plant growth and development, notably the transition from vegetative to productive phase. Combined with light, carbon dioxide, air and water humidity and nutrients, temperature influences plant growth and crop yield. Each factor must be properly balanced. Temperature affects plants in both the short and long term [17]. In the context of the study, in winter, the maritime influence to the north and the effect of altitude on the mountains inland cause minimum temperatures to drop by 10°C at the Annaba seaside. In summer, average temperatures reach = 25° Celsius.

### 1.3 Urban and demographic evolution

In the article entitled "Detection changes in land occupation and use (between 1984-2021) using 'GEE' and GIS Tools", published in the Indonesian Journal of Social Science Research [9], an in-depth analysis is carried out on the urban and demographic evolution of Annaba, Algeria. The study reveals significant urban expansion since 1984, characterised by an increase in the use of urbanised land, leading to increased consumption of space and particularly impacting green structures such as forests and agricultural land. This urbanisation, primarily attributed to urban planning policy decisions favouring development at the expense of ecological preservation, has been accurately quantified using advanced tools such as Google Earth Engine (GEE) and Geographic Information Systems (GIS). The findings highlight the need for sustainable urban planning practices incorporating green space conservation to mitigate urban heat island effects and ecological degradation.

Since 1998, the population of Annaba has proliferated, from 559,896 to 625,689 in 2008, and is projected to reach about 759,137 by 2030, more than tripling in four decades. Representing 1.79% of the total Algerian population and about 12% of that of the North-East region, this demographic growth reflects a trend observed at both the national and regional levels. However, the irregular distribution of the population, with more than 72% concentrated in the municipality of Annaba and surrounding areas such as El Bouni, El Hadjar and Sidi Ammar, poses significant challenges; the population density was represented in Figure 3 [18].

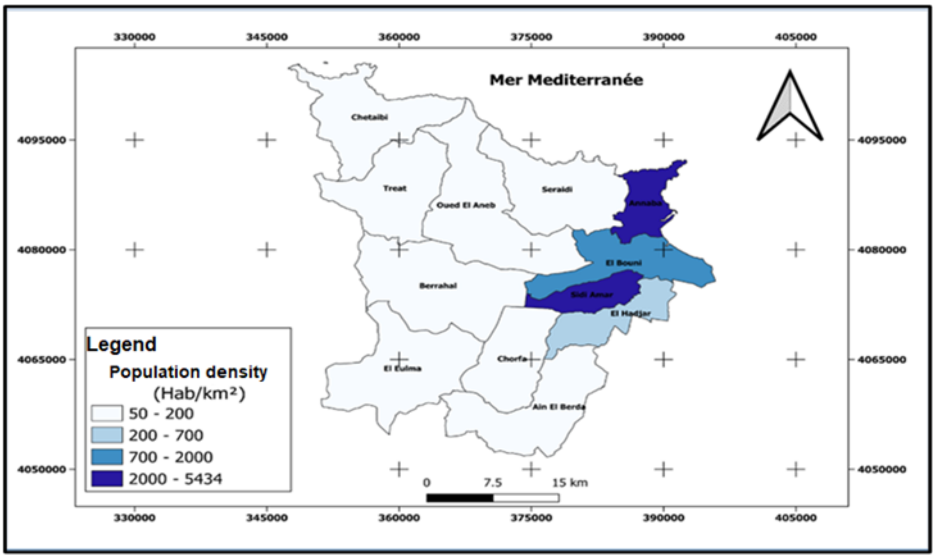


**Figure 3: Variation of population density in Annaba**

These challenges include resource and space management, requiring urgent adaptation to manage this population and spatial growth better. Massive programs for housing, facilities and services, as well as the inevitable expansion of urban areas, accompany this population growth and have a spatial influence on the city, affecting the development of natural resource consumption and focusing attention mainly on green land, especially forests and agricultural land [19].

The impact of urban sprawl and population growth on the quality of life in Annaba is profound and multifaceted. The rapid increase in population has led to intensive urbanisation, marked by a significant increase in the use of urbanised land and a consequent reduction in green space. As illustrated in Figure 04, this urban landscape transformation directly affects the inhabitants' quality of life in several essential ways. The decline of green spaces contributes to the increase in urban heat islands, worsening local temperatures and possibly increasing the prevalence of heat-related illnesses [20]. Green spaces are crucial not only for regulating the urban climate but also for providing spaces for leisure and relaxation, which are essential for the mental and physical well-being of city dwellers [21].

**Figure 4: Urban area in Annaba city.**

## 3. MATERIAL AND METHOD

The primary objective of this study is to investigate the temporal dynamics of Land Surface Temperature (LST) and the Normalized Difference Vegetation Index (NDVI) within Annaba City over three distinct years: 1984, 2004, and 2021. This research aims to quantify the impact of urbanisation on green surface areas and understand how these changes correlate with variations in the city's thermal environment.

### 3.1. Data and equipment used

The influence of green spaces on urban climate is very evident, especially during the dry seasons[22],[23]. For this reason, a series of consecutive multispectral Landsat images were used to investigate the relationship between the Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST) in Annaba City for the period 1984, 2004 and 2021. These specific satellite scenes were selected for their timing and taken during the same seasons and at similar times, ensuring comparable atmospheric and phenological factors. The satellite images' date and characteristics have been displayed in the flow table (table 1.)

**Table 1: Study data sources**

| Data layer | Source | Spatial resolution (m) | Date |
|---|---|---|---|
| **Landsat 5 surface reflectance** | **GEE Dataset (USGS)** | **30** | **26/08/1984** |
| **Landsat 5 surface reflectance** | **GEE Dataset (USGS)** | **30** | **17/08/2004** |
| **Landsat 8. surface réflectance Oli/tırs sensor level 1** | **GEE Dataset (USGS)** | **30** | **16/08/2021** |

This study was processed through the Google Earth Engine (GEE). GEE, a cloud-based platform, facilitated large-scale data analysis, enabling efficient access and processing of remote sensing data to calculate NDVI and extract LST values accurately. Figure 5 shows the flowchart of the method used to analyse the satellite imagery data. This platform's robust processing capabilities allowed for handling extensive datasets without local computational resources, ensuring that data manipulations were both scalable and reproducible [24],[25]. Additionally, QGIS, an advanced open-source Geographic Information System, was pivotal in performing spatial analysis and visualising the intricate relationship between NDVI and LST. Within QGIS, we employed sophisticated spatial analysis tools to overlay processed imagery, conduct detailed comparative studies, and visually represent the data (Figure.05). This enables precise identification and analysis of temporal and spatial variations in vegetation cover and urban heat. This integrated approach using high-resolution satellite imagery, GEE, and QGIS not only streamlined the workflow but also enhanced the accuracy and depth of our urban ecological analysis.

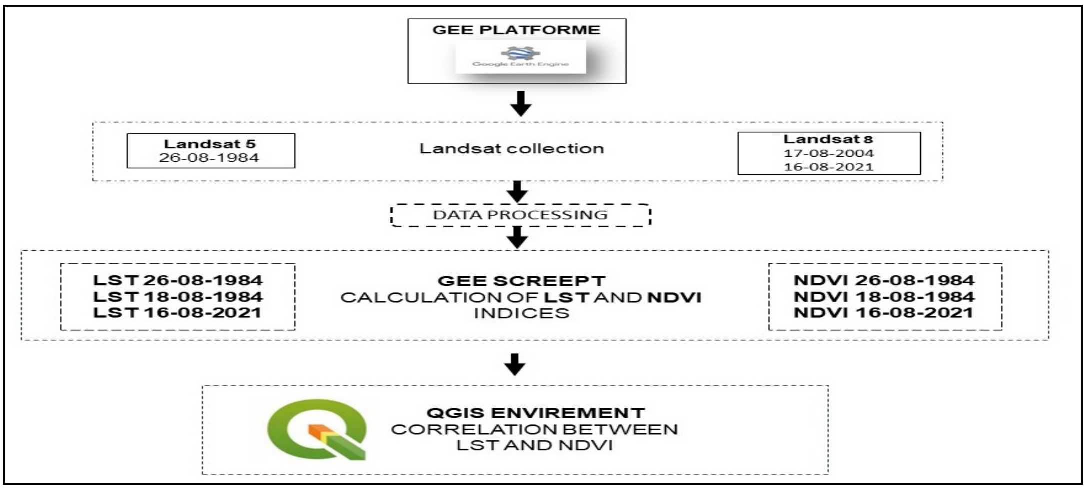


**Figure 5: Flowchart of the method followed in data processing**

### 3.1.1. Normalized difference vegetation index (NDVI)

The Normalised Difference Vegetation Index (NDVI) determines the degree of greenness as a function of the phenological state of the vegetation. It also provides information on inter- and intra-annual variations in greenness, which can be influenced by climatic conditions such as humidity and solid particles in the atmosphere. The NDVI provides information on various biophysical variables that describe variations in vegetation growth and biomass [26]

The Standardised Vegetation Index  is a vegetation index commonly used in remote sensing to study land cover. It highlights the variability of vegetation cover and surface water.

This index identifies healthy vegetation thanks to an apparent reflectance in the near-infrared electromagnetic spectrum. The reflectance of green leaves is about 20% or less in the range of 0.5 to 0.7μm (green to red) and about 60% in the range of 0.7 to 1.3μm (near infrared) [27],[28]. It is crucial to note that NDVI is a scientific measure and must be presented objectively, without any subjective statements. Vegetation and non-vegetation below the 0.5 range reflect the Bare soil. Interpretation of NDVI images will be based on "Table 2".

**Table 2: NDVI classification pixel range**

| Pixel Range | Class |
|---|---|
| <0 | Water |
| 0.03-0 | Bare Soil |
| 0.03-0.3 | Sparse Vegetation |
| 0.3-0.5 | Moderate vegetation |
| 0.5> | Dense vegetation |

In general, NDVI values range from -1 to 1. The index indicates positive values for vegetation, values close to zero for bare soil, and very negative values for surface water. On the other hand, using the NDVI, or normalised difference vegetation index, is mandatory. This is a simple yet effective index for quantifying green vegetation.

In the present work, the NDVI value was calculated from available satellite imagery of the dry seasons of 1984, 2004, and 2021 to study the change in the green structure area of Annaba and its impact on the climate situation.

### 3.1.2. Surface temperature (LST)

Surface temperature, in particular land surface temperature (LST), is a critical aspect that can be affected by urban land use. Reflective properties and surface roughness vary between different land use types, leading to differences in surface temperature[29]. It is, therefore, essential to study precisely the relationship between land use and surface temperature (LST) in order to analyse the natural effects of the latter. In addition, vegetation can effectively influence surface temperature (Weng al. 2004). In this study, the LST data for the chosen periods of the years 1984, 2004, and 2021 was calculated and then compared with the NDVI data of the same zone to understand the relationship between the two parameters in local climate variation and its environmental consequences.

### 3.2 Data treatment and result

To better understand the phenomenon of vegetation recession due to urbanisation and its impact on surface temperatures, we collected samples along the main axis of development of the town (RN16) and a smaller perimeter. Samples were taken from four different locations (Figure 6):

- Zone 01 : The couple ''Medina -colonial city'',
- Zone 02: The renewed city known as 'the Colonne',
- Zone 03: The post-colonial city extension 'ZHUN Plain West',
- Zone 04: The satellite city 'ZHUN(New urban housing area ) of El Bouni'.

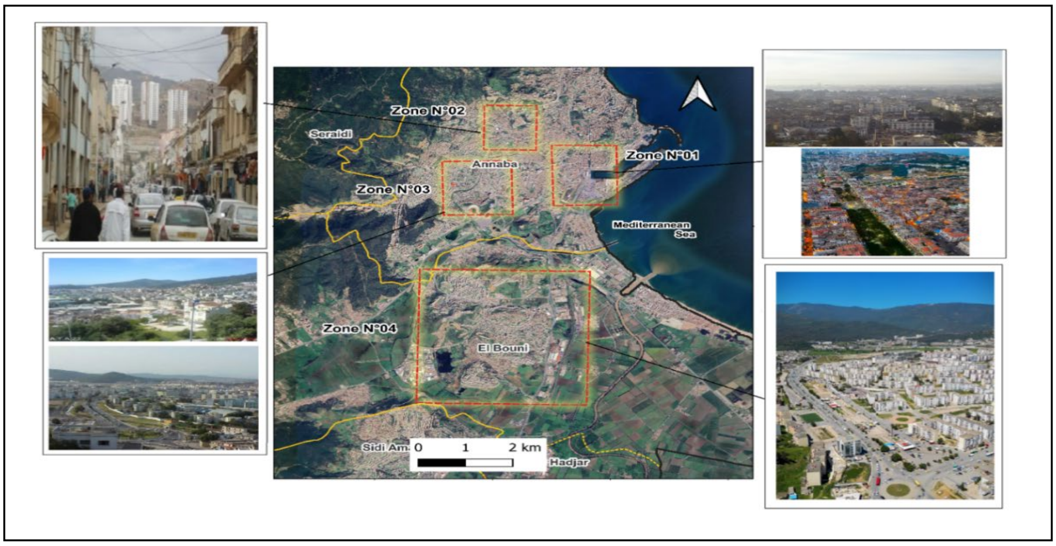


**Figure 6: Repartition of the selected area**

#### 3.2.1 Zone 01: The couple ''Medina -colonial city''

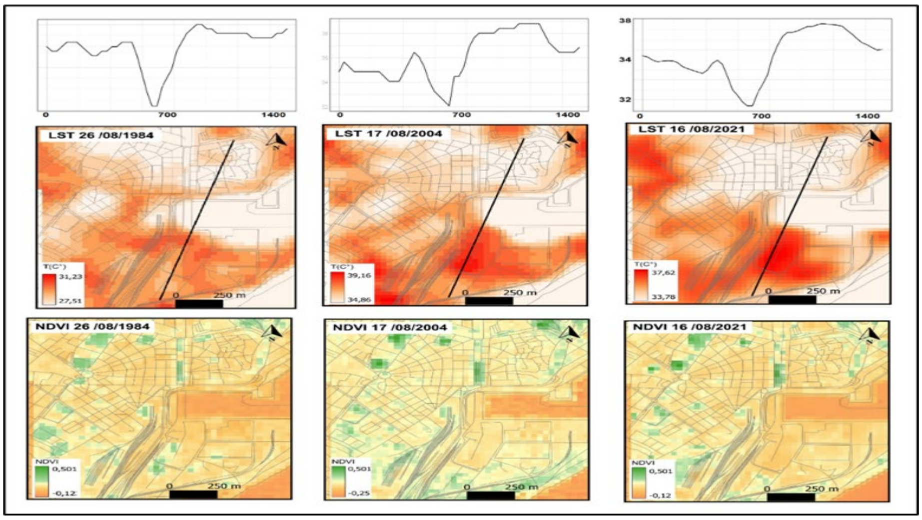


**Figure 7: Variation of land surface temperature LST and NDVI Index between 1984 To 2021 for the Zone 01**

a. Variation temperatures graphs for the periods 1984,2004, and 2021 b. Variation in maximum surface temperatures ''LST'' for the periods 1984.2004 and 2021 c. INDVI Map for the periods 1984,2004 and 2021 (zone 01)

- **Temperature and daytime variation graphs**

The temperature graphs for the medina-colonial town couple (Appendix 1), spanning the years 1984, 2004, and 2021, offer a fine-grained depiction of thermal fluctuations over time within this urban context; these are well illustrated in Figure 7. The 1984 graph delineates a relatively stable thermal signature with moderate temperature excursions between the observed minima and maxima, indicative of a balanced urban microclimate with sufficient vegetative cover and less built-up area to absorb and re-emit solar radiation.

Progressing to 2004, the temperature graph presents a notable alteration in the thermal profile, with heightened amplitude in diurnal temperature variations. The maxima ascend dramatically, suggesting a significant shift towards higher daytime temperatures, characteristic of an intensified urban heat island effect. This shift is congruent with urban development patterns and the proliferation of heat-absorbing materials in the built environment.

The 2021 temperature graph, while still indicative of high diurnal peaks, shows a slight moderation compared to 2004. This moderation could reflect urban greening initiatives or infrastructural modifications aiming to mitigate high temperatures, though the values remain substantially elevated compared to the 1984 baseline. The temperature data for 2021, thus, aligns with the broader understanding of urban climate dynamics and the persistent challenges posed by UHI, as detailed by Taylor and al. (2015) and Lee and al. (2017) [30],[31].

- **Spatial analysis of land surface temperatures (LST)**

The diachronic evaluation of LST for the medina-colonial town couple exhibits a pronounced fluctuation over the observed periods. In August 1984, the LST ranged between 27.51°C and 31.23°C, representing a comparatively undisturbed urban climate. By 2004, there was a marked increase in LST, with values escalating between 34.86°C and 39.16°C. This trend of heightened surface temperatures sustained through to 2021, with LST readings varying from 33.78°C to 37.62°C. This trend illustrates a significant rise in surface temperatures over the studied timeframe, as Jones and al. (2008) and Smith (2012) documented[32],[33]. It is particularly acute in areas characterised by dense urban construction and vigorous industrial or port activities, including the economic zone of the port of Annaba [30], [31]. The data align with findings by Zhou and al. (2014) and Nguyen and al. (2016)[34],[35] which affirm that transformations in land use, notably urbanisation and industrial development, have been instrumental in amplifying the urban heat island (UHI) effect.

- **Correlation with NDVI maps**

Longitudinal analysis of NDVI maps demonstrates variances from -0.12 to 0.501, illustrating a transition from highly urbanised zones with scant vegetation to regions with dense green cover. The NDVI is a well-established remote sensing index for estimating vegetation density and vigour. Negative values typically denote a lack of vegetation, whereas positive values indicate photosynthetically active vegetation. The comparative temporal study of LST and NDVI from 1984 to 2021 uncovers significant urban environmental shifts. The changes in LST values on 16/08/2021 provide evidence for substantial thermal variation, likely linked to urban development's effects and land cover alterations.

The inverse relationship observed between LST and NDVI over time highlights the critical cooling function of vegetation within urban ecosystems. A decrease in NDVI, indicating a loss in vegetation cover, is generally accompanied by an increase in LST. This reflects the diminishment of the urban canopy, which is known to mitigate temperatures through evapotranspiration and shading, a concept supported by Gill et al. (2007)[36]. Such insights are imperative for informing sustainable urban design and planning, ensuring that cities like the historic medina and colonial town pair evolve harmoniously with environmental sustainability directives.

### 3.2.2 Zone 02: LST and NDVI in the "renewed" city »

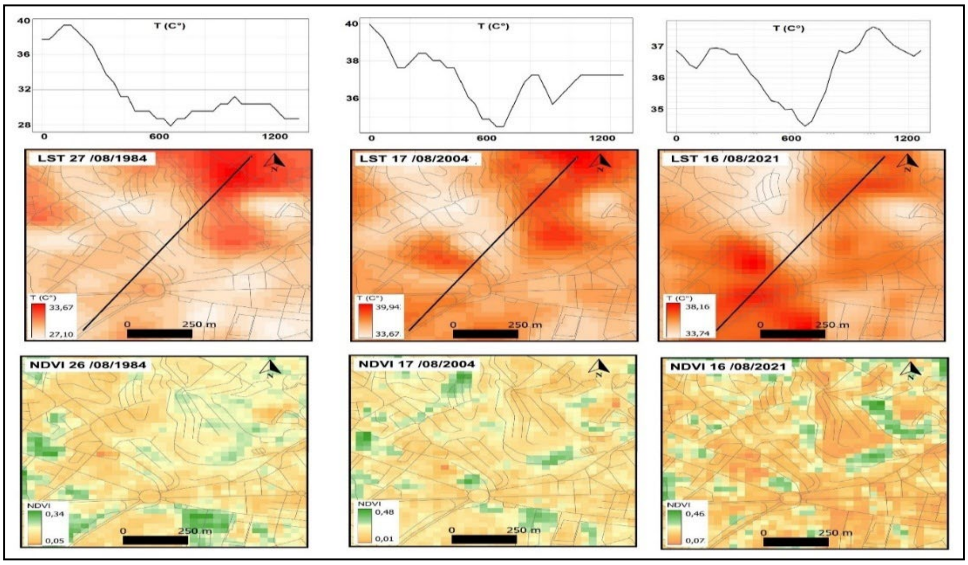


**Figure 8: Variation of land surface temperature LST and NDVI Index between 1984 to 2021 for the zone 02**

## ➢ Temperature and daytime variation graphs

The temperature graphs likely represent diurnal variations correlated with LST spatial data on specific dates. For example, the diurnal range of August 27, 1984, begins with cooler morning temperatures, intensifies to a peak of warmth at midday, and decreases as the evening approaches. This pattern of daily temperature fluctuation has become more extreme over the years, with the urban area experiencing a more comprehensive temperature range due to intensified urban development. These variations are illustrated in Figure 8.

## ➢ Spatial analysis of land surface temperatures (LST)

LST maps reveal a noticeable increase in surface temperatures over time, especially in densely urbanised districts. On August 27, 1984, LST values were moderate, reflecting a less densely developed urban landscape, with maximum temperatures of about 31.23°C. By August 17, 2004, this peak LST had climbed to 39.16°C, which signified a dramatic increase and highlighted the intensification of the urban heat island effect in the urban fabric, which is dense with buildings and impermeable surfaces that accumulate heat. The trend continued until August 16, 2021, when LST records still indicated high temperatures with highs of 38.16°C, although slightly cooler than in 2004, possibly due to mitigation efforts or variations in urban structure. These data are presented in Figure 8.

The increase in LST from 31.23°C in 1984 to 39.16°C in 2004 and a slight decrease to 38.16°C in 2021 can be directly associated with urban development activities. The upward trend highlights the profound impact of urbanisation, particularly the densification of infrastructure, which contributes to the UHI effect. Surfaces such as concrete and asphalt have a high heat capacity and low albedo, resulting in greater absorption and retention of solar radiation, thus increasing the local temperature. The slight decrease in the maximum LST in 2021 could suggest the effectiveness of urban greening initiatives or changes in urban planning that could have been implemented to mitigate the effect of UHI. It is essential to consider that although the maximum temperature has decreased, it is still significantly higher than in 1984, indicating the continuing challenge of UHIs in the face of an obsolete and densified fabric for the renewed parts of the city.

## ➢ Correlation with NDVI maps

The NDVI maps provide a complementary data set, showing the initial high vegetation density in 1984, indicating robust green cover. This green cover has gradually thinned, as evidenced by the 2004 NDVI surveys showing a decline, with this trend increasing in 2021. A clear parallel between the hotspots on LST maps and the most considerable reductions in NDVI values highlights the inverse relationship between urban expansion and vegetation density. As presented in Figure 8.

NDVI values demonstrate declining vegetation cover, significantly reducing from 1984 to 2021. The high NDVI values in 1984 correspond to a more extensive vegetation cover, which has decreased, as indicated by the lower NDVI values in subsequent years. This decline in vegetation could be due to the replacement of green spaces by urban structures during the city's renewal processes. The reduction of green space contributes to rising temperatures due to reduced shading and evapotranspiration and affects urban biodiversity and the overall health of the urban ecosystem.

The inverse relationship between LST and NDVI is a crucial finding. As green space is reduced, vegetation's natural cooling capacity decreases, increasing surface temperatures. This is a classic sign of the UHI effect, where the lack of vegetation exacerbates heat build-up in urban materials. Urban planning that does not sufficiently integrate green infrastructure is likely to foster this trend, highlighting the need to integrate sustainable practices that support the presence of vegetation in urban landscapes.

### 2.2.3 Zone 03: LST and NDVI of the post-colonial city "ZHUN" of the West Plain

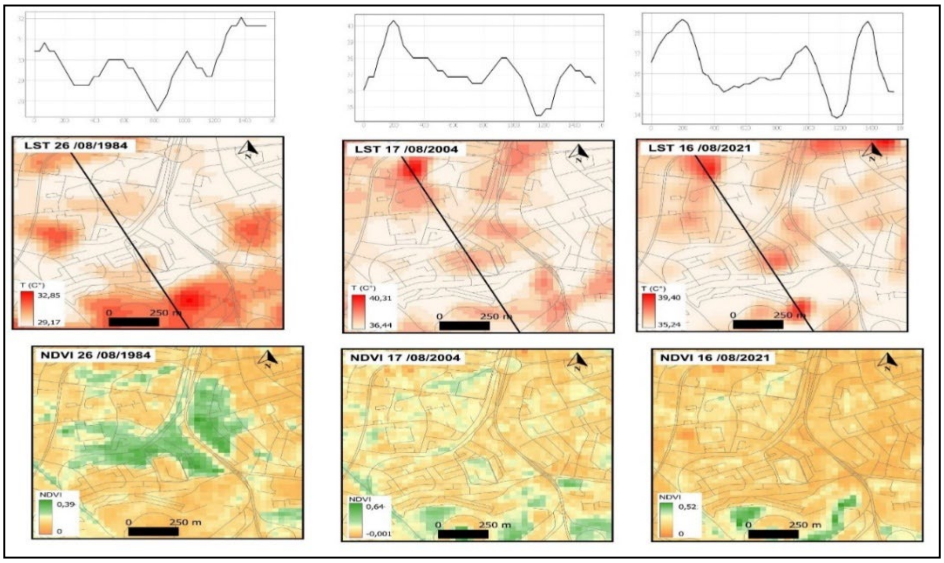


**Figure 9: Variation of land surface temperature LST and NDVI Index between 1984 to 2021 for the zone 03**

- **Temperature and daytime variation graphs**

The temporal temperature profiles for 1984, 2004, and 2021 delineate the diurnal thermal variations within the ZHUN of the West Plain. In 1984, the temperature graph indicated a moderate range, with diurnal temperatures peaking at 32.85°C, suggesting a relatively mild urban climate. By 2004, the graph reflects a substantial increase in maximum temperatures, reaching 40.31°C, highlighting a pronounced escalation in urban heat island intensity. The 2021 graph shows a slight reduction in maximum temperatures, with peaks at 39.40°C, potentially signalling the influence of adaptive urban design strategies or intrinsic fluctuations in local climate conditions, as illustrated in Figure 9.

- **Spatial analysis of land surface temperatures (LST)**

The LST maps across the studied period reveal critical insights into the thermal evolution of the region. The 1984 map indicates a relatively homogeneous temperature distribution with cooler regions correlating with undeveloped or vegetated areas. The significant rise in minimum and maximum LST values by 2004 underscores the impact of urban expansion on local temperatures. In 2021, despite a slight moderation in the LST range, the temperature distribution still reflects elevated values, especially in areas marked by urban density, corroborating ongoing urban heat island effects within the area, presented in Figure 9.

- **Correlation with NDVI maps**

The NDVI data 1984 presents high vegetative density, affirming the existence of substantial green cover at the time. NDVI values evidence this up to 0.39. By 2004, the maximum NDVI slightly increased, suggesting changes in vegetation type, such as introducing more heat-tolerant species or altering land management practices. However, the further decrease in NDVI to 0.52 by 2021 indicates ongoing vegetation cover loss, likely due to intensified urbanisation processes that replace natural landscapes with built environments, impacting the local eco-sustainability and thermal regulation, presented in Figure 9.

### 2.2.4 Zone 04: LST and NDVI of the El Bouni ZHUN

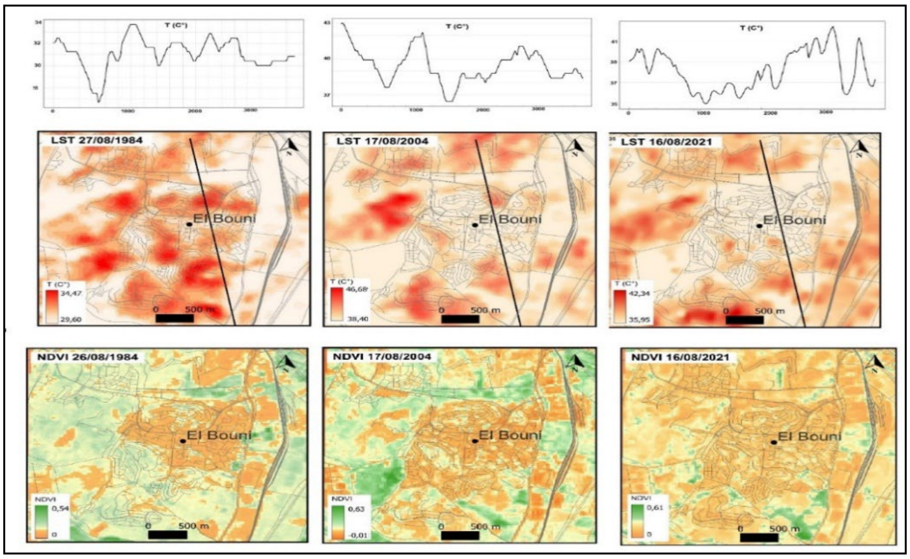


**Figure 10: Variation of land surface temperature LST and NDVI Index between 1984 to 2021 for the zone 04**

- **Temperature and daytime variation graphs**

The diurnal temperature variation graphs provide a dynamic representation of the urban thermal profile at distinct temporal snapshots—1984, 2004, and 2021. These graphs elucidate the intraday thermal flux within the ZHUN of El Bouni, offering valuable insights into the interplay between urban development and climatic behaviour, as shown in Figure 10.

The 1984 temperature graph shows a more moderate and consistent temperature range throughout the day, corresponding to a less developed urban landscape, where natural land cover potentially facilitated a stabilised thermal environment. The morning temperatures start more excellent and rise to midday peaks, following a natural solar radiation pattern before cooling again towards the evening, suggesting effective nocturnal heat dissipation.

Progressing to the 2004 and 2021 graphs, a noticeable amplification in temperature swings is evident, with higher peaks and less pronounced cooling periods. This pattern indicates a disruption in the natural thermal equilibrium, likely due to increased urban surface area and reduced vegetative cover. The sharp temperature spikes suggest that urban materials with high thermal mass, concrete, asphalt, and the like, absorb and re-emit solar radiation more intensely, which impacts the diurnal temperature range and contributes to the urban heat island effect. These aspects are also illustrated in Figure 10.

The intensification of these temperature fluctuations over time underscores the necessity for a comprehensive understanding of urban thermodynamics in planning and developing sustainable urban spaces. With global temperatures rising, the data indicates an urgent need for strategies incorporating thermally responsive materials, designs, and urban vegetation to mitigate these effects and ensure urban resilience against heat stress.

- **Analysis of land surface temperatures (LST) in the El Bouni ZHUN**

The temporal progression of LST within El Bouni's Urban New Habitat Zone (ZHUN) reflects significant climatic shifts over the examined intervals. The 1984 data presents moderate temperatures with a minimum of approximately 29.17°C and a maximum near 32.85°C. A substantial rise is observed by 2004, with average temperatures soaring to about 40.31°C and peaking at 43.44°C, indicating an escalation of the urban heat island phenomenon likely a product of intensified urban sprawl and densification. In 2021, there is a notable though slight decrease in maximum temperature to 39.40°C, suggesting either a partial reversal of the trend or the effect of implemented urban cooling measures. Despite this reduction, temperatures remain substantially higher than the 1984 baseline, underscoring ongoing thermal stress within the urban fabric (Figure 10).

- **Correlation with NDVI maps**

Complementary NDVI maps serve as a vegetative barometer against changing LST values. The initial high NDVI readings in 1984, peaking at around 0.39, signify abundant vegetative cover, which diminishes notably by 2004 and further by 2021, where the maximum NDVI recedes to about 0.52. The downward trajectory of NDVI corresponds to the areas experiencing the most pronounced LST increases, highlighting an inverse relationship indicative of vegetation's mitigating effect on surface temperatures. The trajectory suggests that the loss of vegetative cover due to urban expansion and potential changes in land management practices is a driving factor behind the increased thermal retention that characterises urban heat islands.

### 2.3 General discussion

The analysis of Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI) changes in Annaba City from 1984 to 2021 across four distinct zones— Medina-Colonial town couple, Renewed City ('The Colonne'), Post-Colonial City Extension ('ZHUN Plain West'), and Satellite City ('ZHUN d'El Bouni')—reveals a clear impact of urbanisation and the reduction of green spaces on surface temperatures. In Zone 1 (Medina-Colonial couple ), LST increased from 27.51°C to 31.23°C in 1984 to 34.86°C to 39.16°C in 2004, with a slight moderation to 33.78°C to 37.62°C by 2021. Similarly, in Zone 2 (Renewed City 'The  Colonne'), LST rose significantly from 31.23°C in 1984 to 39.16°C in 2004, with a minor reduction to 38.16°C by 2021. In Zone 3 (Post-Colonial et al.' ZHUN Plain west'), maximum LST increased from 32.85°C in 1984 to 40.31°C in 2004, then slightly reduced to 39.40°C in 2021. Zone 4 (Satellite City 'ZHUN d'El Bouni') experienced the sharpest increase, with LST rising from 29.17°C in 1984 to 43.44°C in 2004, followed by a decrease to 39.40°C in 2021.

The significant influence of the urban heat island effect, where urbanised areas with less vegetation and more built-up surfaces absorb and retain more heat, has increased surface temperatures across these zones. The decline in NDVI values indicates a substantial reduction in vegetation cover, exacerbating the rise in temperatures. Vegetation plays a crucial role in cooling urban areas through shading and evapotranspiration, and its loss has severe implications for urban climate regulation.

Higher surface temperatures adversely affect the quality of life in urban areas, leading to discomfort, health issues such as heat stress, and increased energy consumption for cooling. Moreover, reducing green spaces negatively impacts air quality, biodiversity, and the city's overall aesthetic and recreational value. The slight moderation in LST observed by 2021 in some zones suggests that urban greening initiatives and adaptive urban planning can effectively mitigate the urban heat island effect. Therefore, it is essential to increase green structures, implement green roofs and walls, and use thermally responsive materials in urban design to enhance urban resilience against heat stress. The study underscores the need for integrating green infrastructure in urban planning to improve thermal comfort and sustainability. Policymakers should prioritise developing and maintaining green spaces, implementing regulations to limit impermeable surfaces, and promoting sustainable building materials and designs. By addressing these issues, urban planners and policymakers can enhance the livability and sustainability of Annaba City, ensuring it evolves in harmony with environmental and climatic considerations.

## 4. CONCLUSION

The significant urban expansion observed in Annaba has resulted in noticeable environmental impacts, particularly the rise of the urban heat island (UHI) phenomenon and the degradation of green infrastructure. This study highlighted the central role that green structures play in regulating urban temperatures and promoting ecological sustainability in regions experiencing rapid and widespread urbanisation.

The in-depth analysis of Land Surface Temperature (LST) and the Normalized Difference Vegetation Index (NDVI) for Annaba from 1984 to 2021 provided a comprehensive perspective on urban and environmental transformations. The daytime temperature profiles demonstrated considerable variability throughout each studied day, which may reflect the combined effects of urbanisation and seasonal climatic cycles.

Examining the LST maps for specific dates highlights a significant increase in maximum temperatures: from 33.67°C in 1984 to nearly 39.94°C in 2004, with a slight reduction to 38.16°C in 2021. This upward trend can be attributed to several factors, including intensified urban development and reduced vegetation, which contribute to the urban heat island effect, where built-up surfaces absorb and radiate more heat than natural areas.

The NDVI maps reveal variations indicating changes in vegetation density over the study period., which may indicate that the vegetation density has remained similar or slightly increased. The relationship between LST and NDVI is generally inversely proportional; an increase in LST is often associated with a decrease in NDVI, reflecting the reduction in vegetation. This negative correlation aligns with the principles of thermodynamics and heat exchange in urban environments.

The study's results emphasise revising urban policies by prioritising creating and preserving green networks. This research concludes that the strategic inclusion of green infrastructure is vital for the thermal regulation of cities and for promoting the sustainability of urban ecosystems. Despite some mitigation efforts, increasing surface temperatures highlights the need for more robust urban planning that prioritises green spaces. The application of statistical techniques further quantifies the essential role of vegetation in moderating urban climates, providing empirical support for integrating nature-based solutions into urban development to mitigate the impact of climate change and urban heat islands. Urban planners and policymakers must use this knowledge to create urban environments that are resilient to current climate challenges and sustainable for future generations.

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