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ANALYSIS OF URBAN HEAT ISLANDS IN THE STUDY OF URBAN ENVIRONMENTAL PROBLEMS BASED ON REMOTE SENSING

 Shahnaz AMANOVA¹, Afag HAJIYEVA², Leyla IBRAHIMOVA³, Firuza JAFAROVA²
¹Faculty of Ecology and Soil Science, Baku State University, Baku, Azerbaijan²Azerbaijan State University of Economics (UNEC), Baku, Azerbaijan³Nakhchivan State University, Nakhchivan, Azerbaijan

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Abstract. As global urbanization accelerates cities increasingly face ecological challenges, most notably the Urban Heat Island (UHI) effect. This study investigates the formation and spatial distribution of UHI's in the cities of Mingachevir, Shirvan and Yevlakh, located in the central region of the Republic of Azerbaijan. Utilizing ArcGIS, the analysis processed Landsat 8 OLI/TIRS satellite imagery from August 2023. The analysis revealed that, despite their relatively small size, distinct urban heat islands have formed in the studied cities. The results demonstrate the effectiveness of satellite-based methods for identifying urban heat islands and can be used to support urban planning, environmental monitoring, and climate adaptation strategies in the region. The results indicate a strong correlation between urban density and thermal concentration, with LST values in urban cores reaching up to 42 °C, which is 2 °C higher than the surrounding rural landscapes. Analysis reveals that industrial zones and areas with low albedo surfaces (asphalt and concrete) are primary drivers of thermal intensity in these cities. To mitigate these effects, the study recommends the implementation of “cool roofs”, the expansion of urban green corridors, and the integration of permeable pavements into local zoning laws. These findings provide a quantitative framework for urban planners and environmental policymakers in Azerbaijan to develop targeted climate adaptation strategies and improve urban thermal comfort.

Keywords: urban heat island, climate action, remote sensing, ArcGIS, Landsat, sustainable cities.

✉Corresponding author. E-mail: shahnaz.amanova@gmail.com

1. Introduction

Urban Heat Islands (UHIs) represent one of the most significant environmental challenges associated with rapid urbanization and climate change (Habibi & Kahe, 2024). This phenomenon significantly impacts the ecological balance and thermal comfort of urban residents. Vegetation plays a crucial role in regulating urban microclimates by providing shade and facilitating evapotranspiration from soil and leaves, which act as natural cooling mechanisms (Peluso et al., 2022). However, when natural landscapes are replaced by impervious materials such as asphalt, concrete, and stone, commonly used in road construction and urban infrastructure, the thermal balance of the surface is disrupted (Khalilov & Eminov, 2024). These artificial materials absorb, store, and re-radiate solar energy more efficiently than natural surfaces, resulting in higher surface and near-surface air temperatures (Mammadov & Abdullayev, 2024).

In addition to surface modification, anthropogenic activities associated with urban life – including traffic, industrial operations, dense building structures, and high population concentration – generate significant amounts of waste heat, further intensifying the urban heat island effect. Although UHIs are often perceived as a predominantly summer phenomenon, they can occur throughout the year, including winter, and at any time of day (Khalilov & Eminov, 2024). The effect is typically most pronounced after sunset, when urban surfaces gradually release heat accumulated during daytime. Clear skies and calm wind conditions further enhance the intensity of heat islands by maximizing solar radiation absorption and limiting heat dissipation through atmospheric circulation (Amani et al., 2025; Bochenek & Klemm, 2020).

The environmental and societal impacts of urban heat islands are substantial. Rising urban temperatures increase the risk of heat-related health problems, including dehydration, heat exhaustion, heat stroke, and, in severe cases,

mortality. Heat has been identified as one of the leading causes of weather-related deaths in many regions over recent decades. Moreover, elevated temperatures lead to increased energy consumption, as urban residents rely heavily on air conditioning and cooling systems, resulting in higher electricity demand and associated economic costs (Cuce et al., 2025). Urban heat islands also contribute to the deterioration of air quality. Increased energy production from fossil fuels and higher electricity demand during warm periods result in greater greenhouse gas emissions. Additionally, elevated temperatures facilitate the formation of secondary pollutants, such as ground-level ozone, through interactions between heat and vehicle exhaust gases (Leal Filho et al., 2021). These combined effects exacerbate environmental pollution and negatively affect urban ecosystems and human well-being.

Numerous studies have examined the characteristics and impacts of urban heat islands in large metropolitan areas worldwide, emphasizing their association with impervious surfaces, reduced vegetation cover, and dense urban morphology (Giorio & Paparella, 2023; Dorward et al., 2023). Research has shown that temperature differences between urban centers and surrounding rural areas can reach 8–10 °C under favorable meteorological conditions and may even exceed 10–15 °C in certain cases (Vujovic et al., 2021; Mikayilov et al., 2025). These temperature anomalies are often spatially displaced from city centers in accordance with prevailing wind patterns (Detommaso et al., 2021; Irfeey et al., 2023).

Despite the growing body of international literature on urban heat islands, most existing studies focus primarily on large metropolitan areas, while small and medium-sized cities – particularly in developing and transitional regions – remain insufficiently explored (Ismayilova et al., 2025). In the Republic of Azerbaijan, systematic studies addressing the spatial characteristics and intensity of urban heat islands in smaller cities are limited. Specifically, the thermal dynamics of inland cities in the Kura-Araz lowland have been largely overlooked in previous research (Sadigov et al., 2026; Sultanov et al., 2025). This research addresses this gap by analyzing urban heat islands in selected cities located in the central part of the country using satellite-based remote sensing methods, thereby contributing to a better understanding of urban thermal environments and supporting sustainable urban planning and climate adaptation strategies.

2. Materials and methods

2.1. Study area

Urban heat islands, which are a global environmental problem resulting from global warming and the intensification of urbanization, were also studied in cities located in the central part of the Republic of Azerbaijan. The study focuses on the central part of Republic of Azerbaijan, specifically targeting the urban centers within the Kur-Araz lowland. This region is characterized by a dry subtropical,

semi-arid climate, with hot. Arid summers where temperatures frequently exceed 35 °C.

The absolute height of the relief in the Kur-Araz lowland, which is the study area, is below sea level in most areas (Amanova et al., 2024). These areas cover approximately 2/3 of the Kur-Araz lowland (Figure 1).

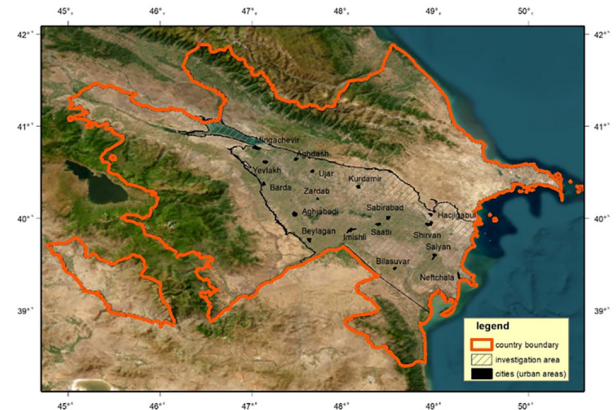


Figure 1. Study area

The research was conducted across several cities, including Hajigabul, Shirvan, Neftchala, Salyan, Saatli, Imishli, and Zardab. These cities are primary industrial and agricultural hubs where urban morphology consists predominantly of built-up zones and impervious surfaces (asphalt and concrete) with relatively limited green spaces. The urban boundaries were precisely delineated based on the “State Land Cadastre” and high-resolution spatial data to differentiate between built-up areas and surrounding rural landscapes.

2.1.1. Data collection and preprocessing and Land Surface Temperature (LST) calculation

Landsat 8 OLI/TIRS Collection 2 Level 1 satellite imagery acquired in August 2023 was used for this study. To ensure data integrity, the raw images were subjected to systematic radiometric calibration and atmospheric correction using the Dark Object Subtraction (DOS) method to eliminate aerosol interference. Geometric corrections were verified against reference topographic maps to ensure sub-pixel spatial alignment.

Brightness temperature (T) was calculated from $TOAr$ using band-specific thermal constants $K1$ and $K2$:

The $TOAr$ values were calculated using the following equation:

$$TOAr = M \times D + B, \quad (1)$$

where: $TOAr$ is the top of atmospheric radiance, M is the radiance multiplier, B is the radiance add value, and DN represents the digital number of each pixel. The M and B values were obtained from the Landsat 8 metadata files (Cordeiro et al., 2023).

The following equation was used to calculate $NDVI$:

$$NDVI = \frac{(NIR + RED)}{(NIR - RED)}. \quad (2)$$

The $TOAr$ values were converted to surface temperatures in degrees Kelvin (Crocé et al., 2021). Surface emissivity (ϵ) was estimated from the $NDVI$ index for each pixel, using the standard equation:

$$T_{kelvin} = \frac{K2}{\ln\left(\frac{K1}{TOAr} + 1\right)} \quad (3)$$

Emissivity values were then incorporated into the LST calculation to account for land cover variations.

2.2.2. Urban Heat Island (UHI) analysis

Urban heat islands were quantified using the standardized equation:

$$UHI = \frac{(LST - LSTm)}{SD} \quad (4)$$

where: LST is the land surface temperature of a given pixel, $LSTm$ is the mean LST of the study area, and SD is the standard deviation of LST . Calculations were performed separately for urban and rural areas to capture spatial variability in temperature distribution.

2.2.3. Data processing

All calculations, including $TOAr$ conversion, brightness temperature, emissivity correction, and UHI computation, were performed using GIS and image processing software. Raster analysis, reclassification, and map generation were conducted entirely within the GIS environment, ensuring accurate spatial representation of LST and UHI patterns across the study area.

3. Results and discussion

Heat islands were studied in many urban landscapes. In this case, data from the Landsat 8 satellite were used. First, a surface temperature map of the study area was compiled using the 4th, 5th, and 10th bands of the Landsat 8 satellite. Then, the heat island was analyzed and mapped on this basis. Urban heat islands were studied in detail in the urban landscapes of Hajigabul, Shirvan, Neftchala, Salyan, Saatli, Imishli, and Zardab.

In addition to surface temperature, $NDVI$ values were calculated for each area to assess the relationship between vegetation cover and UHI intensity. Lower $NDVI$ values, indicating reduced vegetation, corresponded to higher UHI values, demonstrating that impervious surfaces significantly contribute to urban warming. The study areas also include regions with moderate traffic and small-scale industrial activities, which may locally increase surface temperatures and contribute to the observed heat islands. The color legend in all figures represents temperature differences in degrees Celsius, with warmer colors indicating higher LST relative to surrounding areas, based on standardized temperature intervals rather than arbitrary selection.

Studies conducted in the city of Zardab show that the temperature difference is more intense in the urban area

than in the surrounding rural settlements. Thus, while this indicator in the city is $(-1) - 1^\circ\text{C}$, in the surrounding villages this indicator is $(-1.63) - 0^\circ$ (Figure 2). This pattern aligns with the $NDVI$ results, where urban areas show lower vegetation indices compared to rural villages, explaining the greater heat accumulation in the city. Comparisons with similar studies in other semi-arid cities indicate consistent trends, where reduced vegetation and dense urban surfaces increase UHI intensity.

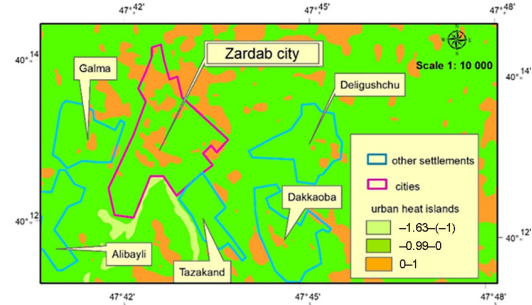


Figure 2. Formation of heat islands in Zardab city and surrounding areas

The urban landscapes where urban heat islands are most intensively observed are the cities of Shirvan and Hajigabul. This difference intensifies as one moves eastward from these urban landscapes. The main reason for this is the moderating influence of the Kura River in the west (Figure 3). Compared to other cities, Shirvan and Hajigabul exhibit the highest LST differences, which correlate with lower $NDVI$ values and higher building density. These results are consistent with prior studies in similar geographic settings, demonstrating that proximity to water bodies and urban planning patterns strongly affect UHI formation.

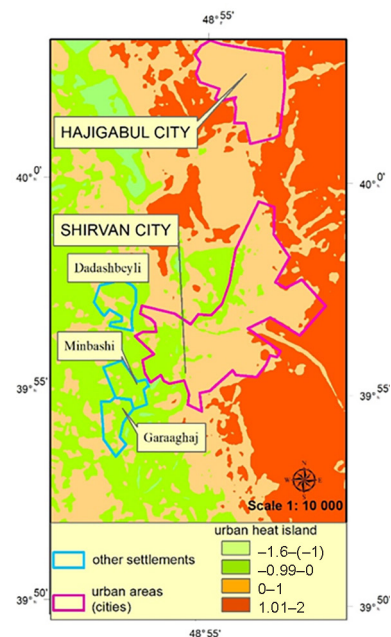


Figure 3. Formation of heat islands in the cities of Hajigabul and Shirvan and surrounding areas

The main factor that weakens the heat island effect in Salyan city is the influence of the Kura River. Here, the temperature difference is observed between 0–1 °C (Figure 4). Vegetation cover in Salyan is higher in areas closer to the river, which is reflected in higher NDVI values and correlates with lower UHI intensities.

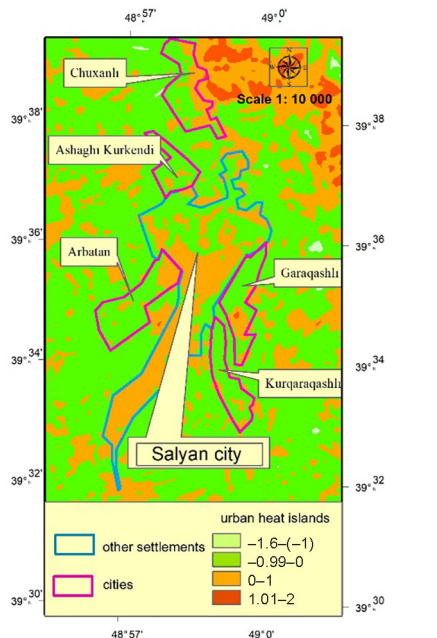


Figure 4. Formation of heat islands in Salyan city and surrounding areas

In Saatli, one of the less densely populated urban landscapes, the weak heat island effect can also be clearly observed. Compared to the villages of Narimankend, Giragly, Musali and Mollaevazli, the difference here varies between 0–1 °C. However, in the villages this indicator is negative (Figure 5). The lower population density and higher vegetation cover contribute to the weaker UHI effect. Traffic and industrial influence in this city are minimal, further supporting these results.

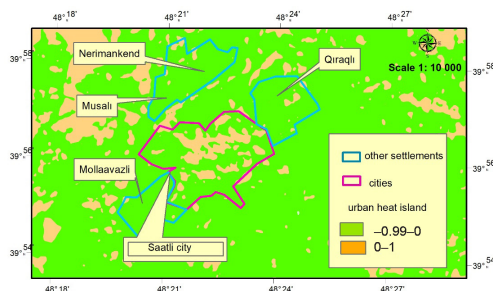


Figure 5. Formation of heat islands in the city of Saatli and surrounding areas

Like the more densely populated cities of Shirvan and Hajigabul, Neftchala also exhibits a pronounced heat island effect. The difference becomes more pronounced the further away from the Kura River bank (Figure 6). NDVI data confirms that vegetation decreases away from the

river, which is associated with higher surface temperatures. These findings highlight the combined effects of urban density, river proximity, and vegetation on UHI formation.

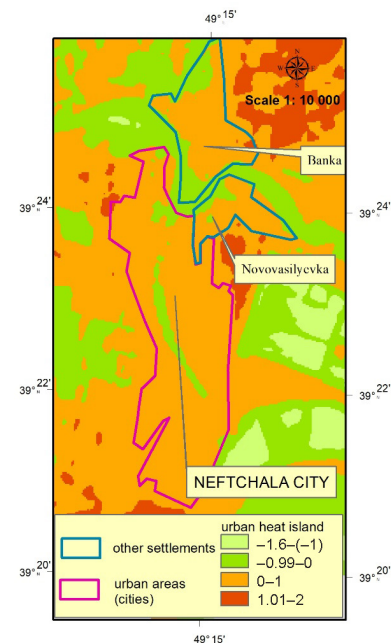


Figure 6. Formation of heat islands in the city of Neftchala and surrounding areas

Heat island analysis in the Imishli urban landscape, located on the banks of the Araz River, shows that the temperature in the city differs by 1 °C compared to the surrounding villages (Figure 7). This aligns with NDVI observations, indicating that vegetation and land cover significantly influence local temperature differences. Compared to other studied cities, Imishli shows moderate UHI intensity, likely due to its proximity to the Araz River and lower urban density.

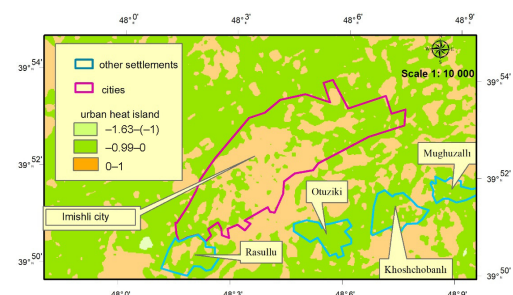


Figure 7. Formation of heat islands in Imishli city and surrounding areas

Comparative analysis shows that in Salyan and Zardab, located along the Kura River, the cooling effect of the river weakens the UHI effect by 1–1.5 °C. Shirvan and Hajigabul are the most active heat islands in the region due to high building density and distance from the river.

Overall, the results indicate that cities with lower vegetation (lower NDVI), higher building density, and limited proximity to rivers exhibit stronger urban heat island

effects. Comparisons across the seven cities reveal both similarities and differences: Hajigabul and Shirvan show the highest UHI intensities, while Salyan and Saatli show the lowest. These differences are attributable to a combination of river influence, urban density, vegetation cover, and local anthropogenic activities. The integrated analysis of NDVI and LST provides a clear explanation of the observed heat patterns and establishes a link between land cover characteristics and UHI formation. LST reached its maximum (42 °C) in Shirvan city, especially along industrial hubs and major highways. This is a result of the additional anthropogenic heat load created by transportation and industrial activities.

4. Conclusions

The analysis of land surface temperature and Urban Heat Islands (UHIs) in the central cities of the Republic of Azerbaijan, including Hajigabul, Shirvan, Neftchala, Salyan, Saatli, Imishli, and Zardab, using Landsat 8 satellite imagery, NDVI calculations, and GIS-based mapping, has revealed that urban areas exhibit temperatures 1–3 °C higher than their surrounding rural settlements. The most prominent factor contributing to this phenomenon is the prevalence of impervious surfaces, particularly asphalt roads and dense built-up areas. In addition, proximity to rivers such as the Kura and Araz significantly mitigates the UHI effect, with urban areas closer to these rivers displaying lower temperature differences.

NDVI analysis indicates that areas with reduced vegetation cover correspond to higher UHI intensities, demonstrating the critical role of green spaces in regulating urban microclimates. This relationship suggests that strategic planning of vegetation in urban areas can effectively reduce heat accumulation. In particular, the introduction of shade-providing trees, drought-resistant leafy species, and the integration of small parks within high-density zones can help lower surface temperatures and enhance residents' thermal comfort.

This study represents the first systematic assessment of urban heat islands in these specific cities of Azerbaijan, providing a baseline for future monitoring and urban planning initiatives. The findings can inform local decision-makers in implementing targeted interventions, such as optimizing green space distribution relative to urban density, incorporating river-adjacent cooling zones, and prioritizing vegetated areas in newly developing neighborhoods.

Future research could expand this analysis to additional small and medium-sized cities in Azerbaijan and neighboring regions, evaluate seasonal and interannual variations in UHI intensity, and explore the combined effects of industrial activity, traffic density, and urban morphology on surface temperature patterns. Such studies will contribute to a comprehensive understanding of urban heat dynamics in semi-arid climates and support the development of sustainable urban climate adaptation strategies.

The DOS (Dark Object Subtraction) atmospheric correction and NDVI-based surface emission model applied in the study allowed us to determine sharp temperature differences in an arid climate with an accuracy of 0.5 °C. It has been found that the Kura and Araz rivers mitigate urban heat islands by 1.2 °C to 1.8 °C. Surface temperatures increase by an average of 0.4 °C for every 500 meters away from the riverbank. Considering the arid climate of the region, the application of xerophytic plant species that require little water (e.g., *Elaeagnus angustifolia* – fragrant, *Tamarix* – yulgun) and reflective materials (cool roofs) on the roofs of buildings is proposed as the most efficient thermal regulation method. This work creates the first “Heat Island Map” database for small cities in the interior regions of Azerbaijan, and this data can be used in the preparation of “Climate Adaptation Plans” for local urban planning departments. In the future, this methodology is planned to be expanded to model the individual impact of industrial emissions and traffic density on thermal energy and applied to the entire Caspian region.

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