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Article

Study of the Thermal Comfort in the Holy Sites, Makkah

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Abstract

This study investigates spatial and temporal variations in thermal comfort conditions across the Holy Sites of Mina, Arafat, and Muzdalifah using multi-temporal land surface temperature (LST) analysis for the years 2014, 2024, and 2025. Satellite-based thermal and optical imagery were integrated with GIS techniques to assess surface thermal behavior and its relationship with land cover characteristics. Urban Heat Island (UHI) patterns were examined through LST mapping, while vegetation and built-up intensity were quantified using the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Built-up Index (NDBI), respectively. The results reveal pronounced spatial heterogeneity in surface temperatures across the Holy Sites, with higher LST values consistently associated with developed areas, road networks, and extensive paved surfaces. Arafat exhibits the highest thermal stress due to its large open paved areas and limited vegetation cover, whereas vegetation-covered zones show noticeably lower surface temperatures. Long-term thermal trend analysis indicates localized warming trends in intensively developed areas, particularly in Mina, while cooling or stable trends are observed in less modified zones, especially in parts of Muzdalifah. The findings highlight the critical role of land cover composition and surface modification in shaping thermal conditions within large-scale religious gathering environments. This study provides an evidence-based framework to support climate-sensitive planning and thermal comfort enhancement strategies in the Holy Sites, contributing to improved environmental management and alignment with Saudi Vision 2030 and the Guests of God Service Program.

Keywords: Thermal Comfort; Urban Heat Island; Land Surface Temperature; Holy Sites; NDVI; NDBI; GIS.

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1. Introduction

1.1 Background and Significance

Urban heat island (UHI) is a widely recognized phenomenon in which urbanized environments exhibit higher temperatures than their surrounding rural areas as a result of land cover transformation, dense built-up structures, and modified surface thermal properties (Oke, 1982). The replacement of natural surfaces with impervious materials such as asphalt and concrete alters surface energy balance, increases heat storage, and reduces evapotranspiration, leading to elevated surface and near-surface temperatures (Oke, 1987). These thermal conditions contribute to increased energy demand, reduced outdoor thermal comfort, and heightened health risks, particularly during extreme heat events (Voogt & Oke, 2003).

The surface manifestation of this phenomenon, commonly referred to as the surface urban heat island (SUHI), is typically assessed using land surface temperature (LST) derived from thermal remote sensing data (Artis & Carnahan, 1982). Unlike air temperature measurements collected at meteorological stations, LST provides spatially continuous information that captures the thermal behavior of different surface materials and land cover types (Van de Griend & Owe, 1993). As a result, satellite-derived LST has become a fundamental variable in urban climate studies and SUHI assessment across diverse geographic and climatic contexts (Qin et. al., 2001).

Remote sensing and Earth observation technologies offer a robust framework for monitoring SUHI patterns due to their ability to provide consistent, multi-temporal, and spatially comprehensive datasets (Jiménez-Muñoz & Sobrino, 2003). Among available satellite systems, Landsat data have been extensively used for LST retrieval because of their long temporal record and suitable spatial resolution for urban-scale analysis (USGS, 2017). However, accurate LST retrieval requires careful consideration of surface emissivity, which varies according to vegetation cover, soil conditions, and built-up materials (Sobrino et. al., 2004). Consequently, emissivity estimation represents a critical step in ensuring the reliability of thermal remote sensing-based analyses (Voogt, 2004).

Numerous studies have demonstrated that vegetation plays a significant role in mitigating surface temperatures through shading and evapotranspiration processes (Oke et. al., 2017). Vegetation-related indicators such as the Normalized Difference Vegetation Index (NDVI) have consistently shown a negative correlation with LST, highlighting their cooling effect in urban and peri-urban environments (Berdahl & Bretz, 1997). In contrast, impervious and built-up surfaces tend to retain and re-radiate heat, intensifying SUHI effects, especially in compact and highly urbanized areas (Voogt & Oke, 1998). These relationships form the theoretical foundation for linking SUHI patterns with land use and land cover characteristics.

In hot-arid and desert climates, SUHI impacts are often amplified due to high background temperatures, limited vegetation cover, and extensive paved surfaces (He et. al., 2007). Cities located in such environments frequently experience pronounced surface temperature contrasts between urban and non-urban areas, particularly during summer periods (Zhou et. al., 2013). Remote sensing-based studies conducted in Saudi Arabian cities have confirmed the effectiveness of satellite-derived LST in identifying SUHI intensity and spatial variability under hot-desert climatic conditions (Miky, 2019).

Beyond conventional urban settings, thermal stress associated with SUHI poses critical challenges in environments characterized by mass gatherings and intensive pedestrian activity. Prolonged outdoor exposure combined with high surface temperatures can significantly affect walkability, crowd movement efficiency, and public health outcomes (Oke, 2006). In this context, the integration of thermal remote sensing with planning and management frameworks has been increasingly recognized as a necessary approach to mitigate heat-related risks (Bonafoni et. al., 2015).

The holy sites of Mina, Arafat, and Muzdalifah constitute a unique spatial environment where seasonal population density increases dramatically during the Hajj period. These sites are characterized by extensive paved surfaces, temporary infrastructure, and pedestrian-dominated movement patterns, which collectively increase vulnerability to thermal stress (Fallatah & Imam, 2023). Previous studies have demonstrated the value of satellite-derived LST in assessing thermal conditions within the holy sites and in examining the relationship between surface temperature, vegetation cover, built-up areas, and topography (Addas, 2023).

Despite the growing body of research on SUHI and LST-based analysis, many existing studies focus on single-date observations or limited temporal snapshots. Such approaches may not adequately capture long-term thermal evolution or the cumulative impact of surface modifications and shading interventions. Long-term thermal trend analysis provides a more comprehensive perspective by identifying persistent warming, cooling, or stable thermal behavior over time (Parlow et. al., 2014).

Accordingly, this study investigates long-term thermal dynamics across Mina, Arafat, and Muzdalifah using multi-temporal land surface temperature data spanning the period from 2014 to 2025. By applying pixel-wise linear regression to satellite-derived LST datasets, spatial thermal trends are classified into warming, cooling, and stable categories. This approach enables an improved understanding of thermal evolution within the holy sites and provides evidence-based insights to support thermal comfort enhancement and climate-sensitive planning for mass gathering environments.

2. Study Area and Methods

The study investigates thermal conditions and long-term land surface temperature (LST) behavior across the holy sites of Mina, Arafat, and Muzdalifah in Makkah, Saudi Arabia, which together constitute the main spatial setting of the Hajj pilgrimage and represent one of the most complex seasonal mass-gathering environments worldwide (Fallatah & Imam, 2023). These sites experience extreme short-term population density within a confined spatial and temporal framework, where millions of pilgrims are required to perform religious rituals predominantly in outdoor environments and rely heavily on walking as the primary mode of movement. Such characteristics increase direct exposure to surface thermal conditions and amplify the importance of understanding spatial and temporal variations in land surface temperature as a proxy for thermal stress. The geographical location and spatial extent of the study area, including the boundaries of Mina, Arafat, and Muzdalifah and their spatial relationship within the Makkah region, are illustrated in Figure 1, which provides spatial contexts for all subsequent analyses.

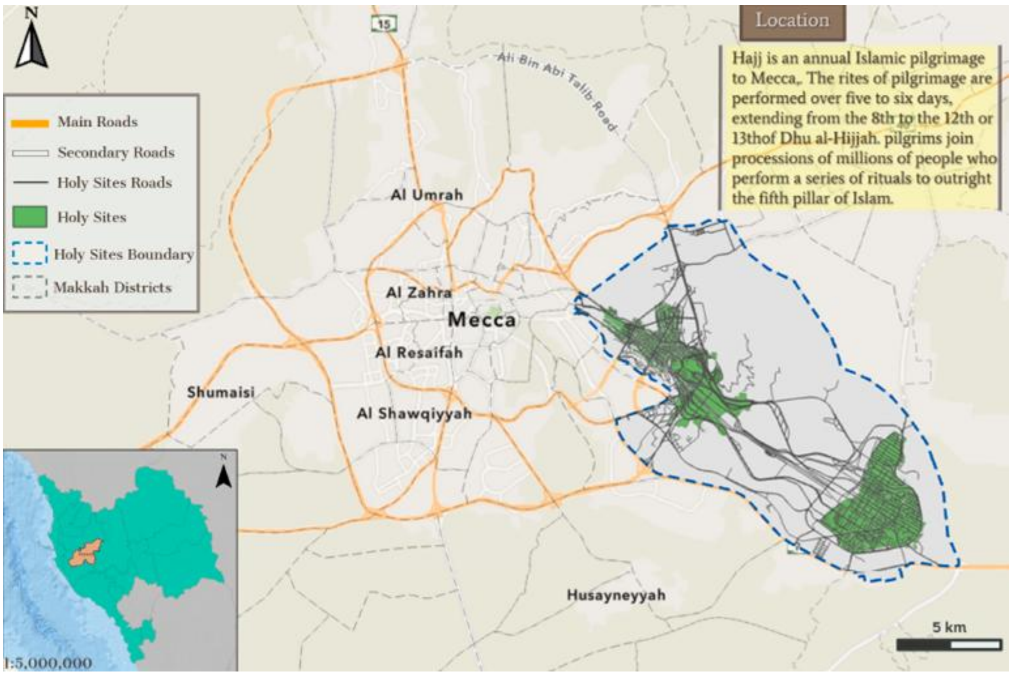

Figure 1: The Location of the Study Area

The study area is located within a hot-arid climatic zone characterized by extremely high air temperatures, intense solar radiation, and low annual precipitation. Under such climatic conditions, surface materials such as asphalt, concrete, and densely arranged temporary structures tend to absorb and retain heat, resulting in elevated surface temperatures that may exceed ambient air temperatures by a considerable margin. International urban and environmental planning literature has consistently highlighted that settlements in arid regions are particularly vulnerable to heat-related risks, especially when urban form and land cover are dominated by impervious surfaces and vegetation is limited (UN-Habitat, 2020). These challenges are further intensified in the holy sites during the Hajj season due to the exceptional concentration of pilgrims over short periods, which places significant pressure on public spaces, pedestrian corridors, and environmental comfort. Official national statistics confirm the scale of these seasonal population surges and underline the unique demographic dynamics of the holy sites during Hajj (GAS, 2023).

From a spatial and functional perspective, each of the three holy sites exhibits distinct physical characteristics that influence surface thermal behavior. Mina is characterized by dense temporary tent structures arranged along narrow valleys, resulting in high surface coverage, reduced airflow, and limited opportunities for thermal dissipation. Arafat consists largely of wide-open plains with sparse vegetation cover and extensive paved areas that accommodate large congregations during peak ritual periods, increasing direct exposure to solar radiation. Muzdalifah represents an intermediate landscape combining open areas with transportation infrastructure and pedestrian routes intensively used during ritual movements. Across all sites, impervious surfaces dominate land cover patterns, while vegetation remains limited, making land surface temperature a critical indicator of thermal conditions experienced by pilgrims.

To assess surface thermal behavior across the study area, multi-temporal satellite imagery from the Landsat program was employed due to its long-term temporal availability, consistent spatial resolution, and established applicability in land surface temperature studies (Fallatah & Imam, 2023). Landsat 8 imagery was selected for three representative years—2014, 2024, and 2025—to capture both long-term thermal behavior and recent surface temperature conditions. For each year, two complementary types of satellite data were processed: thermal infrared imagery for land surface temperature estimation and optical imagery for surface characterization and classification. Thermal data acquired from the Thermal Infrared Sensor (TIRS) were used specifically for LST extraction, while optical bands were used to calculate spectral indices related to vegetation and built-up surfaces. A detailed summary of the satellite imagery used in the study, including sensor type, data type, spatial resolution, and analytical purpose for each year, is presented in Table 1.

Table 1. Satellite data used in the study

Year	Satellite	Data Type	Purpose
2014	Landsat 8	Thermal	Land surface temperature (LST)
2014	Sentinel-2	Optical	(surface classification)
2024	Landsat 8	Thermal	Land surface temperature (LST)
2024	GeoEye	Optical	(surface classification)
2025	Landsat 9	Thermal	Land surface temperature (LST)
2025	GeoEye	Optical	NDVI / NDBI (surface classification)

All satellite images were processed using a unified and consistent workflow to ensure comparability across the study period and minimize methodological bias. Thermal

Band 10 data were clipped to the boundaries of the study area and resampled to achieve spatial compatibility with optical imagery. Land surface temperature was derived following a single-channel approach that involved sequential radiometric and physical transformations. Digital numbers were first converted to spectral radiance, which was then transformed into at-sensor brightness temperature using sensor-specific calibration constants. To account for surface emissivity variations, vegetation-related information was incorporated through the calculation of spectral indices from optical imagery.

The Normalized Difference Vegetation Index (NDVI) was calculated to represent vegetation presence and support the estimation of fractional vegetation cover, while the Normalized Difference Built-up Index (NDBI) was used to indicate built-up intensity and impervious surface distribution. These indices provide essential contextual information for interpreting surface thermal variability and correcting brightness temperature values for emissivity effects. Fractional vegetation cover was derived from NDVI values and used to estimate surface emissivity, which was then applied to correct brightness temperature and derive final land surface temperature values. The complete set of equations applied in image correction, spectral index computation, emissivity estimation, and land surface temperature derivation—along with the thermal trend regression model—are consolidated in Table 2 to ensure methodological transparency and reproducibility, consistent with established practices in thermal remote sensing studies (Fallatah & Imam, 2023).

To evaluate long-term thermal behavior across the holy sites, land surface temperature maps derived for 2014, 2024, and 2025 were integrated and analyzed using a pixel-wise linear regression approach. For each pixel, LST values were regressed against time to quantify the direction and magnitude of thermal change over the study period. The regression slope provides an indication of whether surface temperatures have increased, decreased, or remained relatively stable over time. Based on this slope, surface thermal behavior was classified into warming, cooling, and stable trends, allowing for spatial identification of areas experiencing persistent thermal change. This approach has been widely applied in urban and environmental thermal studies to assess long-term surface temperature dynamics and to support the interpretation of spatial patterns of thermal behavior.

Table 2. Key equations used in the study

Component	Parameter	Equation
Radiometric conversion (Thermal)	Spectral radiance	$L_\lambda = M_L \times DN + A_L$
Thermal processing	Brightness temperature	$BT = \dfrac{K_2}{\ln\left(\dfrac{K_1}{L_\lambda} + 1\right)}$
Vegetation index (Optical)	NDVI	$NDVI = \dfrac{NIR - Red}{NIR + Red}$
Built-up index (Optical)	NDBI	$NDBI = \dfrac{SWIR - NIR}{SWIR + NIR}$
Emissivity support	Vegetation proportion	$P_v = \left[\dfrac{(NDVI - NDVI_{min})}{(NDVI_{max} - NDVI_{min})}\right]^2$
Emissivity	Surface emissivity	$\varepsilon = 0.004\, P_v + 0.986$
Land surface temperature	LST	$LST = \dfrac{BT}{1 + \left(\dfrac{\lambda\, BT}{p}\right)\ln(\varepsilon)}$
Trend analysis	Pixel-wise regression	$LST(t) = a + bt$

The overall methodological workflow adopted in this study—from satellite data acquisition and preprocessing, through land surface temperature extraction and spectral index calculation, to thermal trend analysis and classification summarized in Figure 2. This workflow provides a clear overview of the analytical steps applied and illustrates how multi-temporal satellite data were integrated to assess thermal conditions and long-term trends across Mina, Arafat, and Muzdalifah within a consistent and reproducible frameworks.

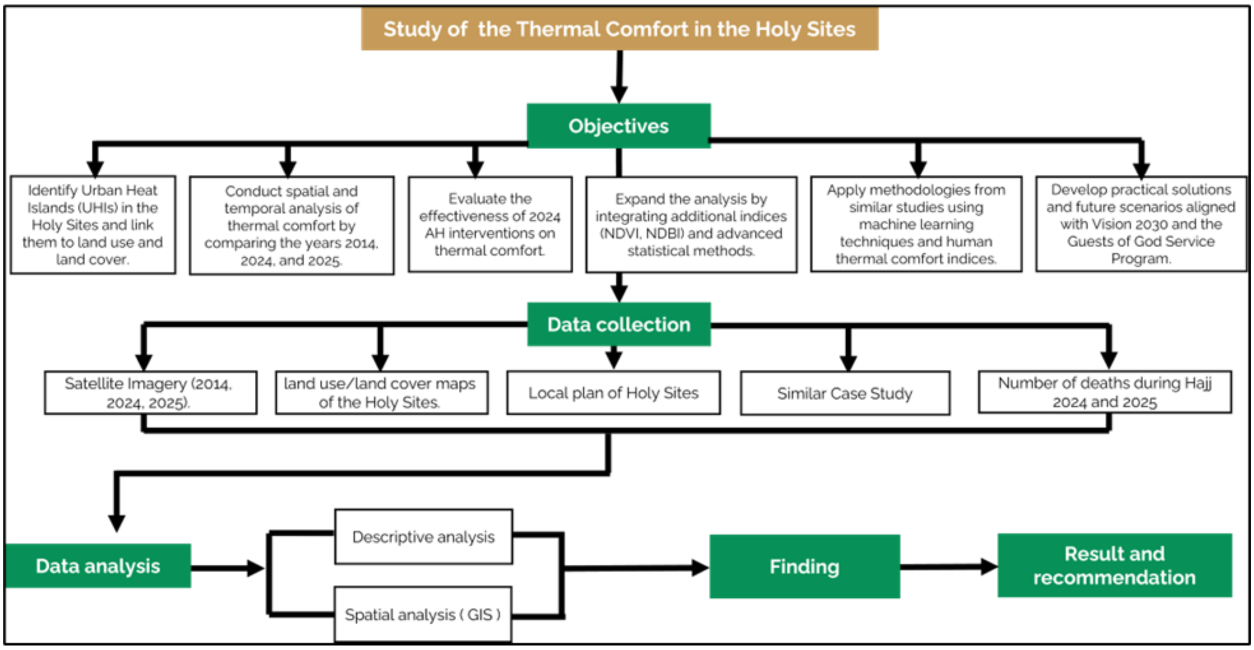

Figure 2. The framework of the proposed methodology.

3. Results

3.1 Spatial Distribution of Land Surface Temperature (LST)

Figure 3 illustrates the spatial distribution of land surface temperature (LST) across the holy sites of Mina, Arafat, and Muzdalifah for the years 2014, 2024, and 2025. The LST maps reveal clear spatial variability within and between the three sites, as well as noticeable temporal differences across the analyzed years. Overall, the thermal patterns demonstrate that surface temperature is not uniformly distributed across the study area; instead, it exhibits localized hotspots and cooler zones that vary in extent and intensity between Mina, Arafat, and Muzdalifah.

Over the three years, higher LST values are consistently observed in intensively used areas characterized by extensive impervious surfaces and dense surface coverage, whereas comparatively lower values appear in more open zones and peripheral areas. In Mina, elevated surface temperatures are prominent in areas associated with dense temporary structures and supporting infrastructure, showing a distinct concentration of high-temperature zones. In Arafat, higher LST values are broadly distributed across large open and paved areas, indicating extensive surface heating across wide spatial extents. Muzdalifah exhibits a mixed thermal pattern, where surface temperature variability reflects the combination of open areas and movement corridors, resulting in localized high-temperature patches alongside comparatively lower-temperature zones.

Temporal comparison across 2014, 2024, and 2025 in Figure 3 highlights changes in both the magnitude and spatial extent of higher-temperature zones. While the general spatial structure of thermal patterns remains recognizable across the study area, the coverage of

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higher LST values expands in several locations in the later years, and some areas show relatively stable thermal behavior across the analyzed period. These results confirm that the holy sites exhibit spatially heterogeneous thermal conditions and that the surface temperature distribution evolves over time, providing a robust basis for subsequent analysis of land cover characteristics, spectral indices, and thermal trend behavior.

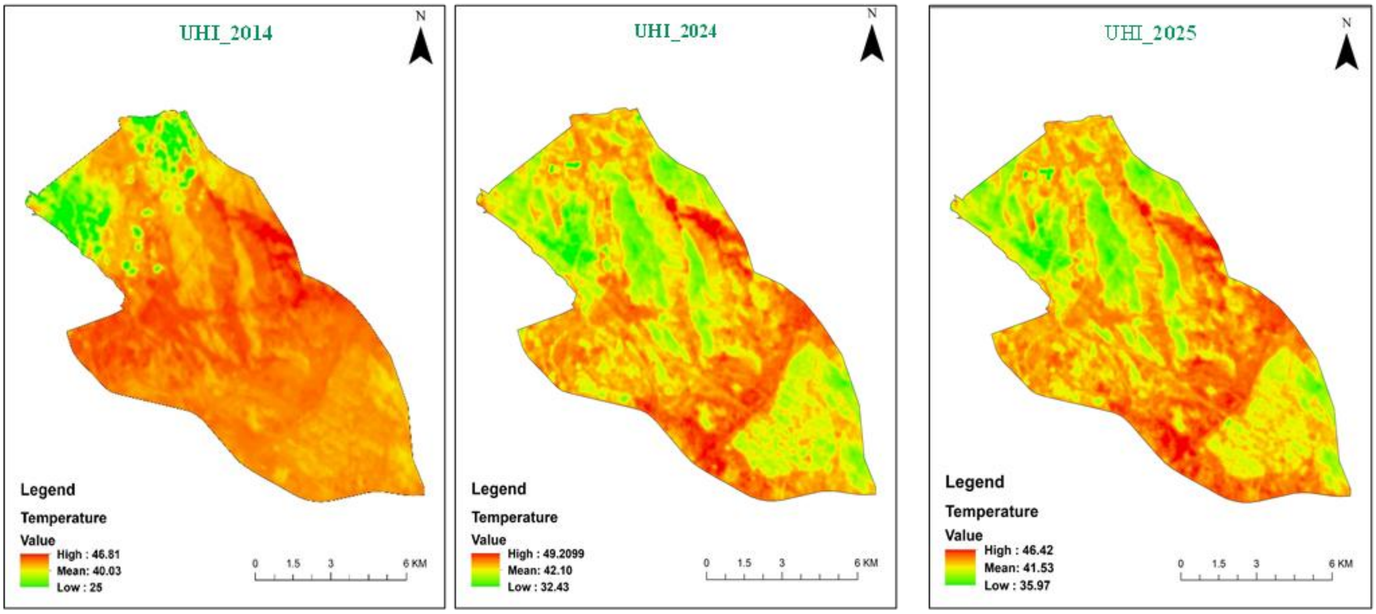

Figure 3. Spatial distribution of land surface temperature (LST) across Mina, Arafat, and Muzdalifah for 2014, 2024, and 2025 .

3.2 Land Cover Classification Results (2014–2025)

The land cover classification results provide essential contextual information for understanding the spatial patterns observed in the land surface temperature (LST) maps. Land cover maps were generated for the years 2014, 2024, and 2025 to examine spatial changes in surface characteristics across the holy sites of Mina, Arafat, and Muzdalifah. The spatial distribution of land cover classes for the three years is illustrated in Figure 4, which highlights both the dominant land cover types and their temporal evolution.

Across the study area, four main land cover classes are identified: developed areas, undeveloped (open) land, road networks, and vegetation. In 2014, undeveloped land constitutes the dominant land cover class across large portions of the study area, particularly in Arafat and Muzdalifah, reflecting the functional role of these sites as open spaces accommodating mass gatherings. Developed areas are primarily concentrated within Mina and selected parts of Arafat, where dense temporary structures, service facilities, and supporting infrastructure are located. Road networks form a distinct linear pattern connecting the three holy sites, while vegetation cover remains limited and spatially fragmented.

The land cover classification for 2024 reveals noticeable changes in the spatial distribution and relative extent of several land cover classes. Developed areas expand in multiple locations, particularly within Mina and along major movement corridors, indicating increased surface modification and infrastructure development. While undeveloped land remains a dominant class across the study area, its spatial continuity shows localized reductions in areas experiencing intensified use. Vegetation cover remains limited and is largely confined to specific zones, with no widespread expansion observed. These spatial patterns are clearly visible in the 2024 land cover map presented in Figure 4.

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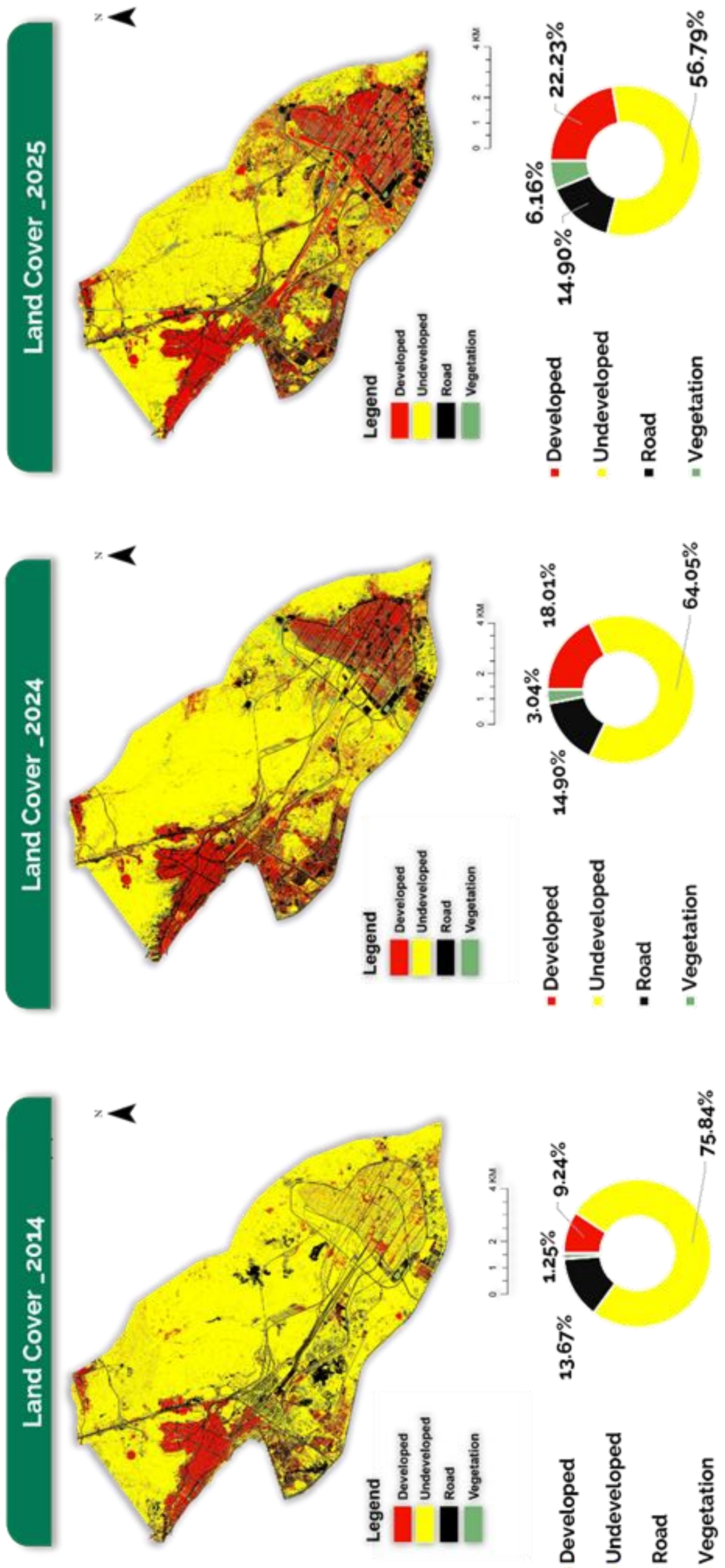


Figure 4. Land cover classification maps for the Holy sites 2014, 2024, and 2025.

In 2025, the land cover classification further emphasizes temporal changes in surface characteristics across the holy sites. Developed and paved surfaces continue to dominate large portions of Mina, while Arafat and Muzdalifah maintain a mixed landscape of open land and infrastructure-related surfaces. Compared to earlier years, developed areas appear more consolidated in certain locations, while undeveloped land continues to occupy extensive areas associated with ritual activities and pedestrian congregation. Vegetation remains the least represented land cover class and is spatially restricted, reinforcing the overall dominance of non-vegetated surfaces within the study area.

Overall, the land cover classification results demonstrate clear spatial and temporal variability in surface characteristics across Mina, Arafat, and Muzdalifah between 2014 and 2025. The observed changes in the extent and distribution of developed and undeveloped surfaces provide an important spatial context for interpreting the LST patterns and thermal trends presented in subsequent sections. By identifying how land cover composition evolves over time, this analysis supports a clearer understanding of the surface conditions associated with observed thermal behavior across the holy sites.

3.3 Land Surface Temperature by Land Cover Type

The variation of land surface temperature (LST) across different land cover types is illustrated in Figure 5, which presents the spatial distribution of LST together with the associated statistical characteristics for developed areas, road networks, vegetation, and undeveloped land for the years 2014, 2024, and 2025. This figure provides a detailed comparison of thermal behavior among land cover classes and highlights both temporal and spatial differences in surface temperature patterns.

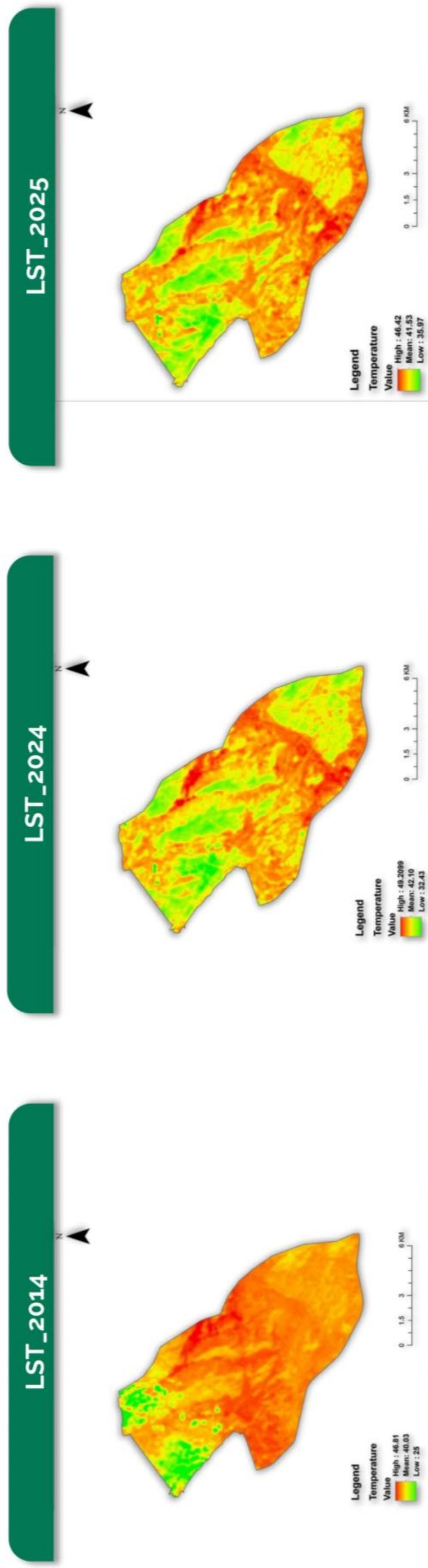
Overall, the results show clear contrasts in LST values between land cover types across the three analyzed years. Developed areas consistently exhibit relatively high average LST values, reflecting their dominance by impervious and intensively used surfaces. Road networks also record elevated surface temperatures, with average values comparable to or slightly higher than those observed in developed areas in some years.

Figure 5's statistical summaries show higher mean and max LST for land cover classes. Undeveloped land has moderate LST with variability over the years, influenced by its spatial extent. Vegetation consistently records the lowest LST, with lower mean temperatures and reduced extremes across 2014, 2024, and 2025, demonstrating its distinct thermal behavior from non-vegetated surfaces.

In addition to differences in average LST values, Figure 5 also demonstrates variation in temperature dispersion among land cover classes, as reflected by differences in standard deviation values. Developed areas and road networks generally show greater thermal variability, while vegetation and undeveloped land exhibit comparatively lower variability in surface temperature. Collectively, these results confirm that land cover type plays a significant role in shaping surface thermal conditions across the holy sites, providing a quantitative foundation for subsequent analyses of spectral indices and long-term thermal trends.

3.4 NDVI and NDBI Results (2025)

Figure 6 illustrates the spatial distribution of NDVI and NDBI across the holy sites of Mina, Arafat, and Muzdalifah for 2025. The NDVI map indicates generally low vegetation values across most of the study area, with relatively higher values limited to small, localized patches. This reflects the restricted and fragmented vegetation presence within the holy sites.



LST_2014

Land Cover	Min. (°C)	Aver. (°C)	Max. (°C)	S.D. (°C)
Developed	28.72	38.32	46.79	4.89
Road	30.06	40.51	46.06	3.92
Vegetation	25.00	40.35	44.75	2.85
Undeveloped	29.82	39.89	46.81	3.92

LST_2024

Land Cover	Min. (°C)	Aver. (°C)	Max. (°C)	S.D. (°C)
Developed	32.43	41.62	47.68	2.34
Road	33.41	42.24	46.94	2.03
Vegetation	35.95	42.22	48.37	1.91
Undeveloped	35.18	42.19	49.21	2.20

LST_2025

Land Cover	Min. (°C)	Aver. (°C)	Max. (°C)	S.D. (°C)
Developed	35.98	42.74	46.39	1.40
Road	38.01	43.25	45.86	1.06
Vegetation	36.66	43.03	46.42	1.09
Undeveloped	36.92	42.82	46.42	1.31

Figure 5. Land surface temperature distribution and statistical characteristics by land cover for 2014, 2024, and 2025 .

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In contrast, the NDBI map highlights extensive built-up and impervious surfaces. Higher NDBI values are concentrated within Mina and along major infrastructure and movement corridors, while lower values appear in more open areas with less surface modification. Together, the NDVI and NDBI patterns in Figure 6 provide a concise representation of surface characteristics in 2025, supporting the interpretation of spatial thermal patterns presented in the previous sections.

3.5 Thermal Trend Analysis (2014–2025)

Figure 7 presents the spatial distribution of long-term thermal trends across the holy sites of Mina, Arafat, and Muzdalifah for the period between 2014 and 2025. The thermal trend map was derived using a pixel-wise linear regression applied to multi-year land surface temperature (LST) data, allowing the identification of areas exhibiting warming, cooling, or stable thermal behavior over time.

The results reveal clear spatial variability in thermal trends across the study area. Areas classified as exhibiting a warming trend are primarily concentrated in specific zones, indicating an overall increase in surface temperature over the study period. In contrast, cooling trends are observed across other parts of the study area, reflecting a decrease in surface temperature values over time. Stable thermal trends appear in areas where surface temperature shows minimal or no significant change throughout the analyzed years. These three trend categories are distinctly illustrated in Figure 7, providing a clear spatial representation of long-term thermal behavior.

Notable differences in thermal trends are evident between the holy sites. Mina shows localized zones dominated by warming trends, while Muzdalifah is characterized by more extensive areas exhibiting cooling trends. Arafat displays a mixed pattern, with cooling, warming, and stable trends distributed across different zones. Overall, the thermal trend analysis highlights the heterogeneous nature of long-term surface temperature changes across the holy sites, complementing the spatial LST distribution and land cover results presented in the previous sections.

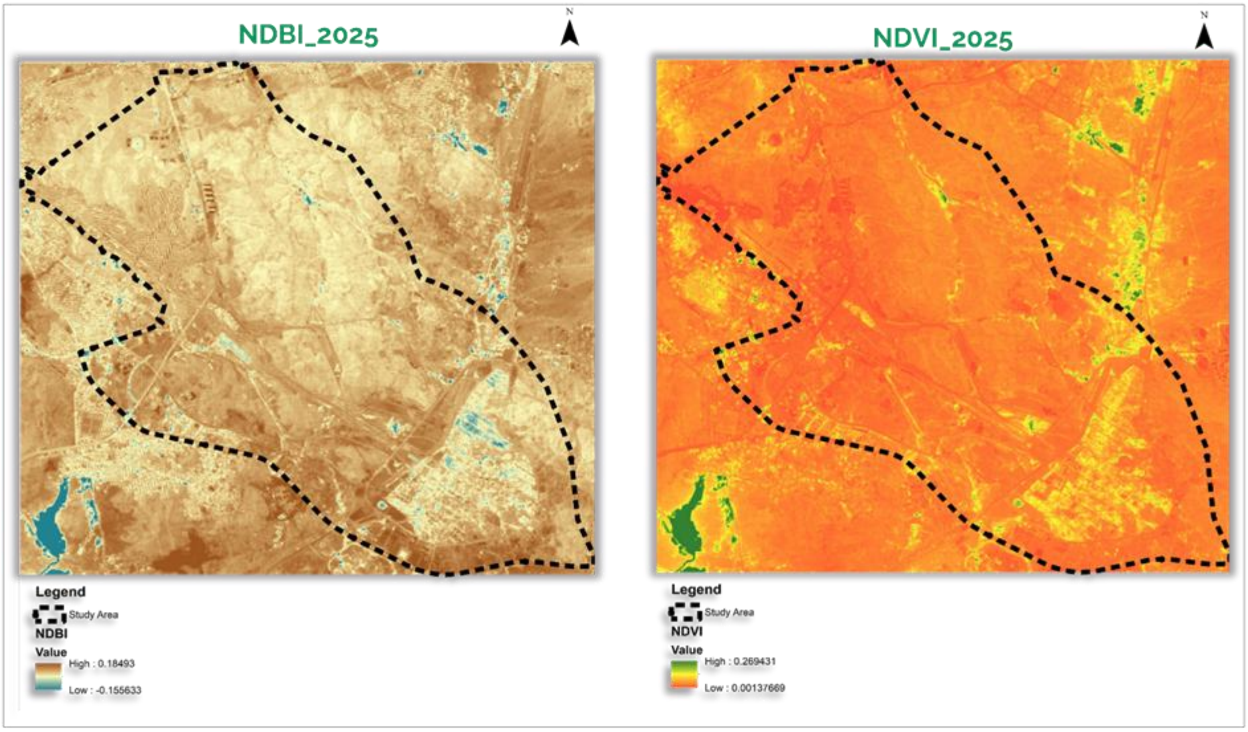

Figure 6. Spatial distribution of NDVI and NDBI across the Holy sites for 2025.

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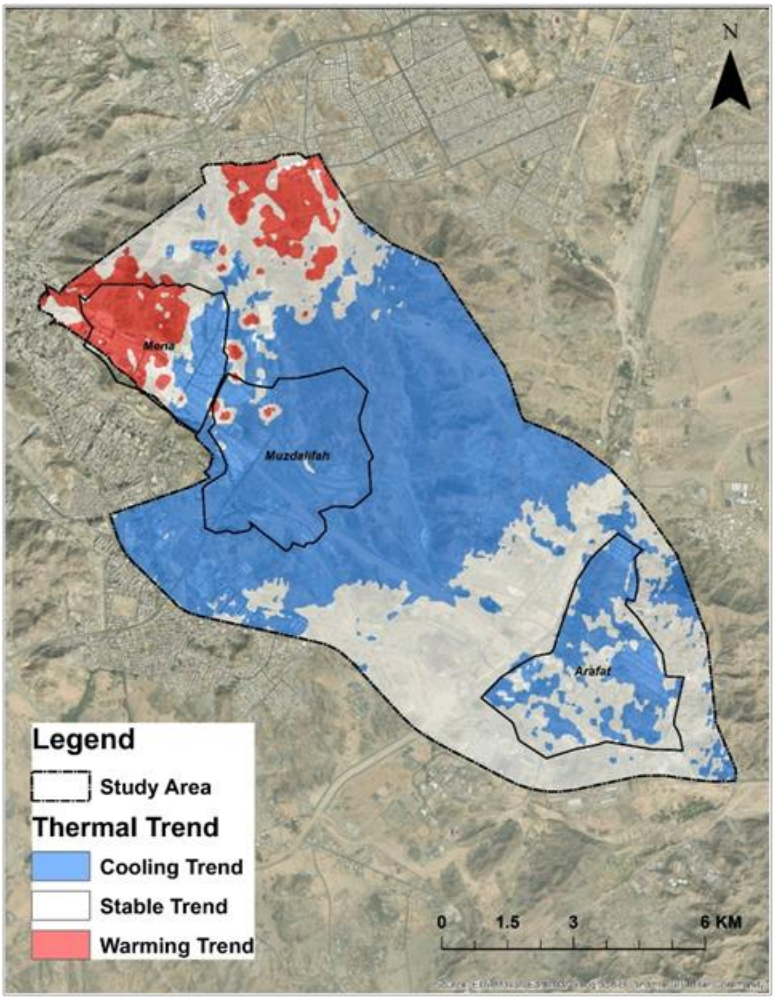

Figure 7. Thermal trend analysis map for the Holy sites (2014-2024)

4. Discussion

The results of this study provide a detailed understanding of surface thermal behavior across the holy sites of Mina, Arafat, and Muzdalifah by integrating land surface temperature analysis, land cover classification, spectral indices, and thermal trend assessment. Unlike conventional urban studies, the study area represents a unique spatial and functional context characterized by seasonal population surges, temporary structures, and extensive open spaces. Nevertheless, the observed thermal patterns reveal strong similarities with established findings in urban climate and land surface temperature research, while also highlighting site-specific characteristics related to the spatial organization and functional use of the holy sites.

The spatial distribution of land surface temperature for 2014, 2024, and 2025 (Figure 3) shows consistently higher LST values in areas dominated by developed and paved surfaces, particularly within Mina and along major movement and service corridors connecting the holy sites. These areas exhibit persistent thermal hotspots across the analyzed years, indicating that surface material composition and intensive land use play a dominant role in shaping surface temperature patterns. Similar associations between impervious surfaces and elevated LST have been widely documented in previous studies, which emphasize the role of surface materials with low albedo and limited evapotranspiration capacity in enhancing heat absorption and retention. The persistence of these spatial patterns across the three study years suggests that thermal behavior in the holy sites is primarily controlled by structural surface characteristics rather than short-term temporal variability.

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Land cover classification results (Figure 4) provide essential context for interpreting the observed LST patterns. The dominance of developed areas, road networks, and extensive undeveloped land reflects the functional requirements of Mina, Arafat, and Muzdalifah, where large open spaces are necessary to accommodate ritual activities, while built-up and paved surfaces support services, circulation, and temporary facilities. The expansion and consolidation of developed surfaces observed between 2014 and 2025, particularly within Mina, correspond spatially with areas exhibiting higher surface temperatures. This relationship between land cover composition and surface thermal behavior is consistent with previous findings that link land cover transitions toward built-up surfaces with increased surface temperatures in rapidly transforming environments. In contrast, the persistence of large undeveloped areas in Arafat and Muzdalifah contributes to more spatially heterogeneous thermal patterns, as reflected in the LST maps.

The analysis of land surface temperature by land cover type (Figure 5) further confirms the strong differentiation in thermal behavior among surface classes. Developed areas and road networks consistently exhibit higher mean and maximum LST values compared to undeveloped land and vegetation-covered surfaces across the analyzed years. This finding aligns with earlier studies demonstrating that built-up and transportation surfaces contribute disproportionately to surface heating due to their physical properties and exposure characteristics. Undeveloped land displays intermediate thermal behavior, reflecting its mixed surface conditions and varying exposure to solar radiation. Vegetation-covered areas, although limited in spatial extent, consistently record the lowest LST values, reinforcing the well-established cooling role of vegetation through shading and evapotranspiration processes. The clear thermal contrasts observed in Figure 5 provide quantitative evidence of how surface composition directly influences thermal conditions within the holy sites.

The NDVI and NDBI results for 2025 (Figure 6) offer additional insight into the surface characteristics underlying the observed thermal patterns. Low NDVI values across most parts of Mina, Arafat, and Muzdalifah indicate limited vegetation presence, which restricts the potential for widespread surface cooling. Vegetated areas appear as small, fragmented patches, confirming the dominance of non-vegetated surfaces within the study area. In contrast, high NDBI values highlight the extensive distribution of built-up and impervious surfaces, particularly within Mina and along major infrastructure corridors. The inverse spatial relationship between NDVI and NDBI observed in Figure 6 is consistent with previous research linking increased built-up intensity with elevated surface temperatures. These spectral indices therefore support the interpretation that surface modification and limited vegetation coverage are key contributors to the observed LST patterns.

Thermal trend analysis for the period 2014–2025 (Figure 7) reveals spatially heterogeneous long-term thermal behavior across the holy sites. Warming trends are primarily observed in areas characterized by sustained surface modification and intensive use, particularly within parts of Mina. In contrast, cooling trends are more evident in areas of Muzdalifah and selected zones in Arafat, where surface conditions remain relatively stable and less intensively developed. Similar spatial differentiation in long-term thermal trends has been reported in previous studies examining the cumulative effects of land cover dynamics on surface temperature evolution. The presence of stable thermal zones further indicates that not all areas within the holy sites experience uniform thermal change, highlighting the importance of localized analysis when assessing long-term thermal behavior in complex environments.

Overall, the findings of this study demonstrate that surface thermal behavior in the holy sites is strongly influenced by land cover composition, surface modification, and long-term spatial dynamics. While the unique functional characteristics of Mina, Arafat, and Muzdalifah distinguish them from conventional urban environments, the observed relationships between land cover, spectral indices, and surface temperature align closely with established urban climate literature. The integration of multi-temporal LST analysis, land cover classification, NDVI and NDBI assessment, and thermal trend mapping provides a robust framework for understanding thermal dynamics in large-scale religious gathering areas. These results contribute to the growing body of research on climate-sensitive planning and thermal comfort assessment in complex human environments and offer a scientifically grounded basis for future investigations and mitigation strategies.

5. Conclusion

This study investigated spatial and temporal patterns of land surface temperature across the holy sites of Mina, Arafat, and Muzdalifah by integrating multi-temporal thermal data, land cover classification, spectral indices, and thermal trend analysis. The results revealed clear spatial heterogeneity in surface thermal behavior between the three sites and across the analyzed years, highlighting the strong influence of surface characteristics and land cover composition on land surface temperature distribution.

Developed and paved surfaces, particularly within Mina and along major infrastructure corridors, consistently exhibited higher land surface temperature values, while undeveloped land showed moderate thermal behavior. Vegetation-covered areas, although limited in spatial extent, recorded the lowest surface temperatures, confirming their role in moderating thermal conditions. The NDVI and NDBI results for 2025 further supported these findings by demonstrating the inverse relationship between vegetation presence and built-up intensity, reinforcing the link between surface composition and thermal behavior.

Thermal trend analysis for the period 2014–2025 indicated spatially differentiated long-term temperature changes across the holy sites, with warming trends concentrated in areas of sustained surface modification and cooling trends observed in less intensively developed zones. These findings emphasize the importance of localized thermal assessment in complex environments characterized by seasonal population dynamics and mixed surface functions.

Overall, the integrated methodological framework applied in this study provides a robust basis for understanding surface thermal dynamics in large-scale religious gathering areas. The findings offer valuable scientific evidence that can support future efforts aimed at improving thermal comfort, guiding surface management strategies, and informing climate-sensitive planning within the holy sites.

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Data Availability Statement: All data generated and analyzed during this study are available from the corresponding author upon reasonable request.

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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