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Proceeding Paper

Investigating the Impact of Temperature Changes on Coastal Heritage Sites Using Remote Sensing †

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Abstract

Coastal heritage assets are crucial to a society's history and must be preserved sustainably, despite their vulnerability to both natural and anthropogenic hazards. Their monitoring is challenging due to the interrelated nature of these attributes. While expert observations and on-site measurements are employed, they cover limited areas over time, whereas remote sensing can assess larger regions more regularly. This study examines the impacts of climate change on Old Town North, a conservation area within Southampton Harbour, UK, designated as "heritage at risk" by Historic England in 2024. Particular focus is given to temperature and moisture variations, which may accelerate material decay and heighten risks. Using a multidisciplinary approach, the study uses satellite data to extract land surface temperatures, monitor coastal changes, and identify vulnerable risk zones. Results show that the conservation area faces multiple pressures, including moisture deficiency, urban sprawl, and increased surface temperatures, that together could hasten the deterioration of heritage assets.

Keywords: temperature change; remote sensing; sustainability; heritage assets; coastal monitoring

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1. Introduction

Coastal heritage sites are invaluable records of human history, yet the modern era threatens them. Many of these sites are situated near the sea, making them vulnerable to climate-related hazards. Today, climate change affects numerous archaeological sites worldwide, with coastal sites close to water already suffering some of the most severe damage from erosion and rising sea levels [1]. In the United Kingdom, home to many coastal heritage sites, including castles, shipwrecks, and historic harbours, authorities have warned that an increasing number of these sites are at risk from ongoing coastal retreat. As a result, protecting them has become one of the greatest challenges for conservation agencies [2]. These observations highlight the global and UK-specific urgency of preserving coastal heritage for future generations. The impacts of climate change on these assets go beyond obvious threats such as flooding and storm surges. Gradual changes in temperature and moisture can seriously undermine the structural integrity of historic sites [3]. Studies note that changes in humidity can increase the frequency of salt crystallisation or mould growth, and temperature–humidity fluctuations can significantly alter the physical and chemical properties of heritage materials [4]. Therefore, gradual climate trends are key factors influencing the stability of coastal heritage structures over time.

Effective monitoring of these climate change-related effects is difficult with traditional methods alone. Conventional monitoring mainly depends on on-site inspections, expert surveys, and in situ measurements, which are time-consuming and often limited in spatial coverage. Conversely, recent advances in satellite remote sensing offer promising solutions for heritage monitoring, providing frequent and large-scale observations that can complement on-site data. Remote sensing has already proven useful in archaeology and cultural heritage management, extending beyond site discovery to support long-term monitoring and analysis [5]. These techniques have been successfully applied worldwide, supplying vital data for managing conservation efforts across diverse environmental and cultural contexts. For example, satellite remote sensing has been widely used in Mediterranean regions to evaluate the effects of climate change on archaeological sites, demonstrating the usefulness of spectral indices in detecting environmental stresses [6].

Multi-temporal InSAR techniques have been employed to monitor deformation and assess structural integrity along the Great Wall of China. A case study of the Shanhaiguan section used PSInSAR and SBAS approaches with high-resolution TerraSAR-X data (2015–2017), revealing localised subsidence in mountainous areas despite the overall stability of the wall corridor—highlighting InSAR's effectiveness in identifying potential hazards in large linear heritage structures [7]. A broader study using SBAS-InSAR over Shanxi Province monitored 896 km of the Ming Great Wall, finding that 24.2% of the corridor experienced subsidence of up to ~10 mm/year, underscoring the potential of SAR for systematic heritage monitoring [8]. These global applications demonstrate the robustness and adaptability of remote sensing in heritage conservation across diverse environmental and cultural contexts. This study aims to contribute to the growing knowledge of how remote sensing can be used to monitor heritage sites affected by environmental degradation, especially in marine-influenced settings. The objectives are to identify climate-related environmental changes and anomalies impacting the area, and to identify at-risk zones. To achieve this, several spectral indices have been utilised to characterise environmental conditions in the coastal heritage conservation area at Southampton Harbour, UK, designated as a site at risk [9].

2. Materials and Methods

2.1. Study Area

The Old Town North, a conservation area in Southampton Harbour designated as "heritage at risk" in 2024 by Historic England [9], was chosen as the study area (Figure 1). Its coastal urban environment makes it highly vulnerable to environmental threats such as flooding, rising sea levels, temperature extremes, and humidity changes, all of which are known to accelerate the deterioration of heritage materials.

Figure 1. The Old Town North study area at Southampton Harbour, UK.

2.2. Monitoring Tools and Indicators

Several remote sensing indices were chosen based on their ability to evaluate relevant environmental stressors. Specifically, the Normalised Difference Moisture Index (NDMI), Normalised Difference Water Index (NDWI), and Normalised Difference Built-Up Index (NDBI) were computed using open-source Sentinel-2 satellite data through the Google Earth Engine [10]. NDMI measures vegetation and soil moisture, calculated as (NIR − SWIR)/(NIR + SWIR). Higher NDMI values indicate greater vegetation and soil moisture, while negative or lower values suggest water stress conditions [11]. NDWI detects the presence of surface water and soil moisture, calculated as (Green − NIR)/(Green + NIR). Higher NDWI values close to + 1 indicate abundant water or saturated surfaces, whereas negative or low values reflect dry or impervious surfaces [12]. NDBI evaluates urbanisation and the extent of impervious surfaces using (SWIR − NIR)/(SWIR + NIR). High positive values denote dense urbanisation, while near-zero or negative values indicate vegetated or water-covered areas [13].

Thermal anomalies on heritage assets can be detected through Land Surface Temperature (LST) derived from satellite observations. The LST was obtained using Landsat-8′s thermal infrared bands with Single-Channel, Mono-Window, and Split-Window algorithms [14–21] to assess thermal stress across the conservation area. These open-source datasets and tools enable reproducible and scalable assessments. NDMI and NDWI were chosen to indicate moisture conditions, measuring vegetation water content and surface wetness, respectively; both are crucial for evaluating drought stress and flood risk. Previous research indicates that moisture indices like NDWI and NDMI decline in hotter, drier environments [22] and NDWI in particular has been used to detect changes in water coverage that reveal or conceal archaeological sites [23]. The NDBI index reflects urban or built-up areas; higher NDBI values indicate expanded built surfaces, often linked to increased LST due to urban heat island effects [14], emphasising how urban sprawl amplifies thermal stress. LST directly measures surface heat, a vital component of climate stress. Mapping LST hotspots near heritage sites helps identify areas at risk of thermal damage, where high temperatures may accelerate material deterioration [5]. Collectively, these four indicators provide a comprehensive overview of environmental conditions, from surface moisture and water presence to urbanisation and heat extremes, offering an integrated understanding of climate-related vulnerability at coastal heritage sites [24].

2.3. Assessment Methodology

The study analysed average conditions and temporal changes from 2017 to 2024. Initially, annual average values of NDMI, NDWI, NDBI, and LST were calculated, capturing the area's long-term environmental state. A change detection analysis compared 2017 to 2024 by calculating differences for each indicator, highlighting significant environmental shifts. Instead of relying on a single dependent variable, this study approaches environmental vulnerability holistically, using combined remote sensing outputs to identify high-risk areas. Each indicator independently provided evidence of environmental stress, avoiding potential multicollinearity issues often found in combined multivariate statistical approaches. Spatial overlaps of low moisture (NDMI, NDWI), high built-up areas (NDBI), and elevated LST were qualitatively integrated using GIS, thus identifying vulnerability hotspots.

2.4. Limitations and Complementary Approaches

While remote sensing is invaluable for monitoring heritage assets, it has limitations, including resolution constraints and the inability to detect subsurface or internal deterioration, such as structural integrity and humidity conditions within buildings [25]. Additionally, atmospheric conditions and shadows can further complicate the accuracy of measurements. Therefore, remote sensing alone is inadequate for comprehensive monitoring. To overcome these limitations, integrating remote sensing with field-based methods is essential. Ground-truthing with site-specific checklists and expert evaluations, routinely employed by heritage management agencies, can significantly enhance monitoring accuracy. Instrumental methods, including in situ sensors for monitoring moisture, temperature, and structural displacement, provide precise local data to validate satellite observations [26].

3. Results and Discussion

3.1. Spectral Indices and Land Surface Temperature

Figure 2 illustrates the mean values of NDMI, NDWI, NDBI, and LST from 2017 to 2024. The NDWI values (Figure 2a) within the conservation area are moderate, approximately 0.1, and similar to those in the adjacent built-up environments. Conversely, the northeastern section just outside the conservation area exhibits significantly low NDWI values of around −0.69, indicative of persistent dryness. In contrast, the southwestern portion of the scene demonstrates the highest NDWI value of 0.59, attributable to the presence of seawater. The conservation area displays low NDMI values (negative range) (Figure 2b), implying diminished vegetation moisture or cover. Minor patches with marginally elevated values (~0.1) are scattered throughout. The northeastern region outside the conservation area shows relatively high NDMI values (~0.33), reflecting moisture retention in the vegetated area, as evidenced by the true colour image (Figure 1). The surrounding regions of the conservation area predominantly exhibit low NDMI values, corroborating the arid or impervious characteristics of the landscape.

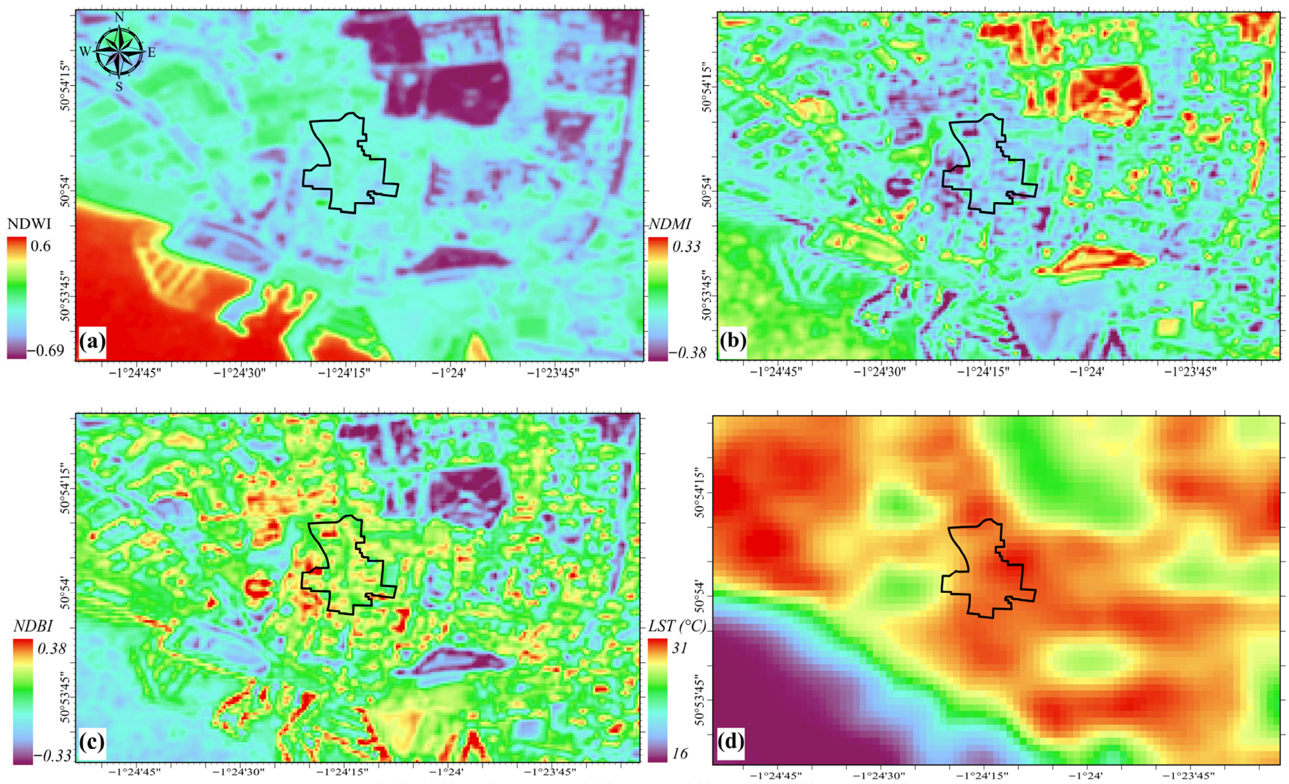

Figure 2. Average values of (**a**) NDWI, (**b**) NDMI, (**c**) NDBI, and (**d**) LST from 2017 to 2024.

Figure 2c illustrates that a considerable proportion of high NDBI patches (~0.38) are located both within and in proximity to the conservation area, underscoring the urbanised or built-up nature of the landscape. Conversely, the northeastern outskirts, which previously exhibited low NDWI and high NDMI, now record the lowest NDBI (~–0.33), affirming the presence of vegetation in this region. From Figure 2d, it is observed that the conservation area demonstrates relatively elevated surface temperatures (~30 °C), rendering it one of the warmest regions within the study area. A gradual increase in temperature is noticeable within the area, with the western section appearing slightly cooler than the eastern section. The northeastern zone outside the conservation boundary maintains a moderate temperature (~22 °C), whereas the northwestern part of the scene exhibits the highest LST values. Several areas exceeding 30 °C are present in this section, likely associated with impervious surfaces or urban heat islands. Based on the observed spatial patterns of NDWI, NDMI, NDBI, and LST, it is reasonable to infer that the conservation area within Southampton Harbour is affected by multiple environmental stressors. The combination of low vegetation moisture, limited surface water availability in adjacent regions, and extensive built-up surfaces may expedite material degradation. The elevated LST values within the conservation area, particularly in the eastern section, further highlight its exposure to thermal stress.

3.2. Change Detection

To evaluate the environmental dynamics and potential impacts of climate change on the heritage conservation zone, a change detection analysis was performed for NDWI, NDMI, NDBI, and LST between 2017 and 2024, as illustrated in Figure 3. The NDWI results (Figure 3a) reveal a slight increasing trend (~0.1) across most of the conservation area, with isolated patches demonstrating a notable increase in up to 0.36, indicating localised improvements in surface moisture conditions. Regarding NDMI (Figure 3b), the analysis shows a predominantly negative trend across the entire scene, including within the conservation boundary, thereby indicating a decline in vegetation moisture content. Conversely, the most significant increase in NDMI (~0.62) is observed in the water body located in the southwestern part of the scene.

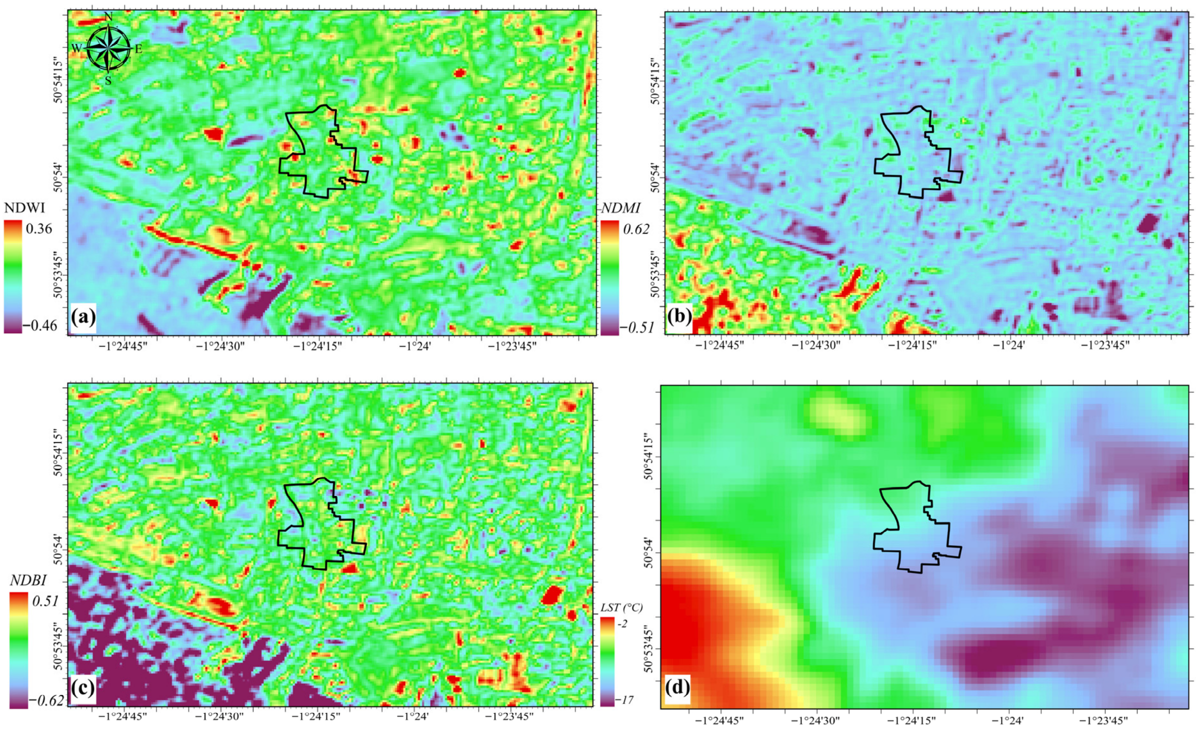

Figure 3. Change Detection analysis of (**a**) NDWI, (**b**) NDMI, (**c**) NDBI and (**d**) LST between 2017 and 2024.

The NDBI change detection (Figure 3c) exhibits a clear positive trend across the majority of the landscape, including within the conservation area, affirming a continuous pattern of urban expansion during the study period. However, a few scattered zones within and surrounding the conservation area exhibit negative NDBI changes, which may suggest land cover alterations or slight de-urbanisation. The most unexpected trend is evident in the LST analysis, which indicates a consistent and substantial decrease across the entire region, with reductions reaching up to 17 °C. This cooling trend is predominantly observed in the eastern section of the scene, while the southwestern water body shows a minimal temperature decline. Within the conservation area, the southern section exhibits a more pronounced decrease in temperature compared to the northern portion.

The analysis of change detection between 2017 and 2024 uncovers a complex environmental trajectory within and surrounding the conservation area. While modest improvements in surface moisture (NDWI) and localised increases in vegetation moisture

(NDMI) are noted, the overall declining trend in NDMI indicates ongoing moisture stress across the landscape. The widespread rise in NDBI reflects substantial urban expansion, thereby accentuating the increasing anthropogenic pressures on the heritage site. A significant cooling trend in land surface temperature has also been observed during this period, potentially attributable to alterations in surface cover, increased local vegetation, or broader climatic modifications in the region. Despite apparent thermal relief, the combined effects of escalating urbanisation and persistent vegetation moisture reduction may continue to pose long-term threats to heritage preservation. This underscores the necessity for integrated, climate-responsive conservation strategies that encompass both physical exposure and overarching environmental transformations.

4. Conclusions and Future Developments

This study presents a remote sensing-based assessment of environmental dynamics influencing a coastal heritage conservation area located in Southampton Harbour, United Kingdom, covering the period from 2017 to 2024. By employing spectral indices (NDWI, NDMI, NDBI) and Land Surface Temperature (LST) measurements obtained from Sentinel-2 and Landsat satellite data, the research delineates spatiotemporal patterns associated with moisture availability, urban development, and thermal stress. These indicators reveal that the conservation area is subjected to multiple pressures, including moisture deficiency, urban sprawl, and elevated surface temperatures, which may expedite the deterioration of materials.

The change detection analysis conducted from 2017 to 2024 further emphasises ongoing environmental transformations, particularly the increase in urbanisation as evidenced by positive NDBI trends and the decrease in moisture as indicated by negative NDMI. These changes are likely to exacerbate existing vulnerabilities. Although a significant cooling trend in Land Surface Temperature (LST) was observed, potentially attributable to evolving surface materials or broader climate fluctuations, this does not necessarily signify a reduced risk. Instead, it highlights the complex interplay between natural and anthropogenic factors that influence the conservation status of heritage sites.

The current research offers preliminary insights into the effects of environmental stressors on coastal heritage areas. While the evidence remains inconclusive at this stage, the findings are consistent with the existing scholarly literature and theoretical expectations. Moving forward, this work contributes to the development of a comprehensive global index designed to evaluate the vulnerability of heritage sites to environmental degradation. Future initiatives will incorporate spectral indicators alongside land deformation and land use change metrics to facilitate scalable, site-specific risk assessments. Such an approach aims to inform policy decisions and promote sustainable heritage management in rapidly urbanising environments.

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