Remote Sensing Applications in Cultural Resource Management: Comparative Insights from Sentinel-2 Imagery and UAV-based 3D Modelling

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Abstract. Cultural Resource Management (CRM) faces persistent threats amid accelerating global urbanization and environmental changes, driving increasing demand for non-destructive remote sensing technologies. To explore the applicability and complementarity of different remote sensing technologies in cultural heritage preservation, this paper employs a comparative case study approach to systematically compare Sentinel-2 satellite image analysis with three-dimensional modeling methods based on UAV photogrammetry. Research indicates that Sentinel-2 imagery, with its advantages of wide coverage, multi-temporal monitoring, and free access, is suitable for macro-scale site surveys and dynamic environmental monitoring. Meanwhile, unmanned aerial vehicle (UAV) technology, characterized by low cost, high spatial resolution, and flexible operation, demonstrates unique strengths in micro-scale detailed documentation and three-dimensional reconstruction of archaeological sites. The two technologies are not competitive but rather complementary in cultural heritage conservation, with specific choices determined by research objectives and management needs. The findings of this study provide guidance for technological decision-making in cultural resource management and indicate that the synergistic integration of multi-source remote sensing data represents a key direction for enhancing the scientific rigor and efficiency of heritage conservation in the future.

Keywords: Cultural Resource Management; Remote Sensing; 3D Modelling

1 Introduction

Against the backdrop of accelerating global urbanization and climate change, cultural heritage faces risks of erosion, destruction, and disappearance. As a critical field coordinating cultural heritage preservation with socioeconomic development, CRM's core mission is to achieve effective protection and sustainable utilization of cultural heritage within this context. However, traditional archaeological survey methods—such as surface surveys and test excavations—while capable of providing precise localized information, are typically time-consuming, labor-intensive, costly, and inherently destructive to sites. These limitations make them ill-suited to meet the urgent demands of modern heritage management for large-scale, rapid, and non-intrusive monitoring.

J. Rak et al. (eds.), *Proceedings of the 2026 11th International Conference on Social Sciences and Economic Development (ICSSED 2026)*, Advances in Economics, Business and Management Research 391,
https://doi.org/10.2991/978-94-6239-701-9_81

Remote sensing technology, with its unique advantages of non-destructive observation, multi-scale monitoring, and high cost-effectiveness, provides revolutionary tools for addressing the aforementioned challenges and is increasingly applied in CRM [1]. At the macro level, satellite remote sensing enables large-scale archaeological site surveys and dynamic environmental monitoring [2]. At the micro level, technologies such as drone photogrammetry and LiDAR facilitate high-precision 3D documentation and detailed modeling of sites, even revealing hidden archaeological features in densely vegetated areas [3]. This multi-scale technical system, spanning from regional surveys to detailed site documentation, collectively forms a solid foundation for the digital preservation of cultural heritage.

Despite the immense potential of remote sensing technology, current research exhibits significant limitations. Most studies focus on demonstrating the application effectiveness of individual technologies—such as satellite remote sensing, unmanned aerial vehicles, or LiDAR—in specific case studies, lacking systematic comparisons and complementary analyses of different technological approaches. This phenomenon hinders the translation of research findings into universally applicable management strategies, thereby limiting their guidance value in complex and dynamic real-world CRM decision-making.

Therefore, this paper selects two representative technical approaches—Sentinel-2 satellite imagery with its extensive coverage and short revisit cycle, and flexible, high-resolution, low-cost UAV photogrammetry—as subjects for comparative study. It systematically analyzes their respective advantages, limitations, and application logic in archaeological site detection within Serbia's Banat region and three-dimensional modeling of Jordan's Udhruh quarry. This study aims to reveal their inherent complementary relationship, providing practical guidance for technology selection and multi-source data fusion in cultural resource management.

2 Literature Review

2.1 The Application Value of Remote Sensing in Cultural Resource Management

The application of remote sensing technology in CRM primarily manifests through its unique advantages of non-destructive monitoring, multi-scale observation, and long-term surveillance. As a non-contact data acquisition method, it effectively avoids the damage caused by large-scale field excavations to the archaeological sites themselves, thereby achieving a balance between preservation and research. Compared to traditional methods relying on manual field surveys and point-based investigations, remote sensing technology offers the capability to acquire data over larger areas, at higher frequencies, and with greater precision, significantly enhancing the overall efficiency of archaeological research and heritage conservation.

At the application level, remote sensing demonstrates value across multiple scales. At the macro scale, it can cover vast areas, thereby support large-scale site surveys and predict potential sites, providing a foundation for comprehensive investigations of cultural heritage resources. At the mesoscale, it enables researchers and managers to monitor environmental pressures surrounding heritage sites, tracking threats posed by urban expansion, agricultural reclamation, road construction, and hydrological changes to cultural landscapes [4]. At the microscale, advancements in technologies such as high-resolution satellites, drones, and 3D laser scanning allow remote sensing to achieve detailed modeling and dynamic monitoring of site topography and even architectural remains. This cross-scale capability endows remote sensing with a flexibility and comprehensiveness in cultural heritage preservation that other methods struggle to match [5].

The practical application value of remote sensing is also reflected in multiple aspects. By analyzing vegetation indices and thermal infrared imagery, researchers can identify subtle differences in vegetation growth and soil moisture caused by buried underground structures, thereby uncovering surface-invisible archaeological remains. For instance, in the Mediterranean region, multi-temporal imagery has been employed to locate ancient settlement sites. At the same time, remote sensing provides a means for monitoring environmental pressures. It can document changes in land use and land cover over decades, revealing the long-term impacts of urbanization, industrialization, and agricultural expansion on archaeological sites. For instance, monitoring the expansion of farmland in the Nile Valley aids in assessing threats to ancient sites. Furthermore, remote sensing data can assist in delineating and updating heritage site boundaries, identifying signs of human disturbance such as looting pits or construction impacts, and providing a scientific basis for conservation and planning. At Pompeii, for example, drone imagery has been employed to analyze visitor activity patterns, thereby improving site protection and tourism management strategies [6]. More importantly, the long-term sequential nature of remote sensing imagery enables it to track the ongoing impact of natural environmental changes—such as climate shifts, flood erosion, or desertification expansion, and the preservation status of archaeological sites. This facilitates a shift from reactive restoration to proactive conservation [7].

2.2 Remote Sensing Technology and Applications

Satellite Remote Sensing. Satellite multispectral and hyperspectral data, with their extensive coverage and rich temporal sequences, have been widely applied in archaeological site surveys and the identification of potential heritage locations. For instance, anomalies in vegetation, soil moisture, and spectral characteristics can reveal sites concealed beneath the surface. Multi-temporal monitoring enables the study of land use changes, erosion processes, and inundation risks, thereby supporting the long-term conservation of heritage sites [8].

Additionally, different sensor types provide complementary information. Synthetic Aperture Radar (SAR) data can penetrate cloud cover, making it suitable for monitoring soil moisture, surface disturbances, and morphological features in cloudy or vegetated areas. Thermal infrared remote sensing reveals buried features through temperature differences between surface and subsurface structures, often used for nighttime observations or environments with significant diurnal temperature variations. Hyperspectral imagery captures finer spectral characteristics, enabling identification of vegetation stress, soil salinization, or mineral composition changes associated with archaeological features.

In recent years, the widespread adoption of high-resolution commercial satellites such as WorldView and GeoEye have enabled researchers to access more detailed spatial information, making it possible to identify small-scale sites, linear surface features, and road remains. Concurrently, the emergence of satellite constellations has significantly enhanced temporal resolution, allowing archaeological research to achieve near-real-time monitoring [9].

In data processing, machine learning and deep learning algorithms are increasingly applied to remote sensing image interpretation and archaeological site detection, enhancing recognition efficiency through automated feature extraction and classification. Combined with GIS spatial analysis, researchers can establish archaeological prediction models across large areas, thereby achieving a shift from "point-based discovery" to "area-based inference."

Aerial and UAV Remote Sensing. Aerial photography and drone imagery provide high-resolution data for small-to-medium scale archaeological site research. Drones, in particular, can capture centimeter-level resolution imagery at low cost and combined with photogrammetry techniques, generate digital elevation models and 3D models. These technologies offer significant advantages in site digitization, detailed surveying, and conservation planning.

Compared to traditional satellite remote sensing, aerial and drone platforms can flexibly adjust flight altitude and angle to capture subtle surface features of archaeological sites, such as trenches, terraces, road remains, or micro-topographic undulations. This enables clear delineation of site contours when ground vegetation is not fully covered or under suitable lighting conditions. Multispectral and thermal infrared cameras mounted on UAVs can also detect vegetation health, surface moisture anomalies, and potential buried features, further expanding their application scenarios.

Drone technology also demonstrates unique advantages in the dynamic monitoring of archaeological sites. Through multi-temporal flights, it can document the condition of sites under seasonal climate changes, flood erosion, or human disturbance, generating high-precision time-series data that aids in the scientific formulation of heritage conservation and restoration measures. Simultaneously, drone-based 3D modeling can be utilized for virtual exhibitions and public education, enabling wider dissemination of sites within digital environments.

LiDAR. LiDAR technology has garnered significant attention in archaeological research due to its ability to penetrate vegetation canopies and directly acquire high-precision surface data. By emitting laser pulses and recording their return times, LiDAR generates high-resolution digital elevation models and digital surface models, revealing microtopography invisible to the naked eye or traditional imagery. Both airborne and terrestrial LiDAR provide crucial tools for archaeological surveys, site preservation, and landscape reconstruction.

At the application level, LiDAR is particularly well-suited for archaeological research in forested or densely vegetated areas. Traditional remote sensing imagery often struggles to identify surface features obscured by vegetation, whereas LiDAR data can filter out vegetation information through point cloud filtering, thereby restoring the true surface morphology. The most iconic application case involves the discovery and mapping of Maya civilization sites in Central America: LiDAR revealed numerous urban ruins, road networks, and agricultural systems concealed beneath the tropical rainforest canopy, profoundly reshaping academic understanding of Maya settlement scales, social structure, and land use patterns [10]. Beyond large-scale surveys, LiDAR also plays a vital role in the detailed modeling and conservation of individual archaeological features.

The most iconic application case involves the discovery and mapping of Maya civilization sites in Central America: LiDAR revealed numerous urban ruins, road networks, and agricultural systems concealed beneath the tropical rainforest canopy, profoundly reshaping academic understanding of Maya settlement scales, social structure, and land use patterns [10]. Beyond large-scale surveys, LiDAR also plays a vital role in the detailed modeling and conservation of individual archaeological features. Ground-based LiDAR enables millimeter-level precision 3D reconstruction of ancient structures, stone carvings, cave murals, and other heritage assets, supporting digital preservation and virtual exhibition of cultural heritage [11]. Concurrently, by integrating time-series data, researchers can monitor surface deformation, erosion, and human-induced damage, making it crucial for site conservation efforts.

2.3 Research Gaps and Challenges

Although remote sensing technology has demonstrated significant value in CRM and archaeological research, existing studies still face multiple shortcomings and challenges. First, at the methodological level, there is a lack of systematic comparison and integration among different remote sensing techniques. Researchers often focus on the application of a single technology, with little exploration of the complementarity of multi-source data and the potential for integrated analysis. This limits the explanatory power and generalizability of research findings. Second, at the case study level, existing research predominantly examines specific regions or individual sites, with study designs leaning toward case-specific approaches. This makes it difficult to establish universal patterns applicable across regions and site types. Given the significant variations in the natural and cultural environments surrounding archaeological sites, the spatial and typological transferability of these findings is relatively limited, diminishing their broader guidance value. Third, at the application level, while remote sensing has achieved remarkable results in site discovery, monitoring, and modeling, most outcomes remain confined to academic exploration and technical demonstration. There is insufficient integration with cultural heritage conservation, management, and policy practices, lacking operational solutions and evaluation systems tailored to practical management needs.

Meanwhile, limitations at the data level are also particularly pronounced. Long-term, continuous remote sensing observation data remains relatively scarce, and no unified standards have been established for data acquisition methods, processing workflows, or precision control. This not only complicates cross-temporal and spatial comparisons but also constrains the deep integration and joint interpretation of multi-source data. These issues mean that while current research provides a solid theoretical and methodological foundation for CRM, it still falls short in terms of systematization, operationalization, and translating academic achievements into practical tools.

3 Case Study I: Archaeological Site Detection with Sentinel-2 Imagery

Estanqueiro et al. conducted a systematic study on the distribution of Late Bronze Age archaeological sites in the southern Carpathian Basin of Serbia's Banat region [2]. This study fully leveraged multispectral imagery data from the Sentinel-2 satellite (November 2019 to July 2022), utilizing Level-2A atmospheric correction products. Through multi-temporal analysis and spectral feature extraction techniques, it successfully identified light-colored soil markings formed by underground relics. The research team innovatively combined multiple vegetation indices (including NDVI, GNDVI, MSR, SAVI, etc.) with principal component analysis (PCA). They conducted spectral separability analysis (M-statistic) on known archaeological site areas and determined that February to May represents the optimal detection window, during which spectral response differences are most pronounced in the early stages of crop growth.

Through systematic remote sensing analysis, the research team identified a total of 102 potential archaeological sites in the Banat and Bačka regions, with 61 located in Banat. Field verification confirmed 22 Late Bronze Age sites and uncovered one new Middle Bronze Age terrace settlement (Barbicus Barugaska Humka). Verification results indicate that 81.82% of the sites contain Late Bronze Age surface artifacts, 40.91% include medieval artifacts, and 31.82% feature Sarmatian period artifacts. Additionally, Neolithic (18.18%) and Iron Age (13.64%) artifact distributions were identified. These findings not only confirm the effectiveness of Sentinel-2 data in detecting large-scale sites (20–100 hectares) but also demonstrate the potential of multispectral data in distinguishing cultural heritage from different periods.

This study fully demonstrates the multiple advantages of Sentinel-2 data in archaeological research: extensive coverage, short revisit cycle (5 days), and free open access, making it particularly suitable for systematic monitoring of large-scale archaeological sites. The research also confirms the unique value of multi-temporal analysis in identifying hidden sites. By tracking annual vegetation growth variations, it can effectively reveal the distribution patterns of underground remains. However, the study also highlights the limitations of 10-meter spatial resolution in identifying small-scale sites (e.g., structures with diameters less than 25 meters). It further emphasizes the challenge of distinguishing soil markers from natural landforms, recommending that field surveys be conducted for verification. This methodology provides crucial technical support for cultural heritage management, demonstrating significant application value, particularly in rapid surveys and long-term monitoring.

4 Case Study II: UAV-based Low-cost Photogrammetry for 3D Site Modelling

Emaus and Goossens conducted a study on three-dimensional modeling of archaeological sites using low-cost aerial photography technology in the Udhruh region of Jordan's Petra hinterland [3]. This study focused on Roman-era quarry sites, employing kites as aerial photography platforms in conjunction with standard consumer-grade digital cameras to achieve high-precision 3D digital documentation of the sites despite their complex topography and challenging field conditions. The study area is situated in a typical desert environment, where the surface is covered with gravel and sharp flint, and vegetation is thorny, presenting special requirements for the selection of aerial photography platforms.

For data acquisition, the research team designed a dual-line controlled kite aerial photography system equipped with a Panasonic DMC-FT4 camera. Through a meticulously engineered suspension bracket and shock absorption device, the camera maintained excellent stability during flight. Utilizing a 60-meter control line, the kite could fly at an altitude of 50-60 meters, enabling manual operation to achieve aerial coverage. Image acquisition employed a timed automatic shooting mode. While real-time monitoring of captured footage was not possible, data integrity was ensured by increasing the number of shots taken.

Data processing was conducted using Agisoft PhotoScan software, generating dense point clouds and 3D models through Structure from Motion (SfM) algorithms. The study specifically addressed image tilt and blurring caused by wind effects, utilizing the software's masking function to optimize processing results. To evaluate model accuracy, the team deployed ground control points (GCPs) using a Topcon GTS-601C total station. Calculations confirmed the final model achieved an accuracy of 1.1 centimeters, fully meeting archaeological documentation requirements.

The study successfully generated a high-precision digital elevation model and orthophotography of the quarry site, providing detailed documentation of its topographic features and morphological details (see Fig. 1). These outputs not only furnish rich spatial information for archaeological research but also offer crucial support for conservation planning. Particularly for archaeologically complex sites like Udruga, this methodology demonstrates unparalleled advantages over traditional surveying techniques.

The advantages of this method are primarily reflected in three aspects: First, it offers significant cost-effectiveness, with the total investment in aerial photography equipment far lower than that of professional drone systems. Second, the kite platform demonstrates strong environmental adaptability, unaffected by rugged terrain and easy to maintain. Third, it provides high flexibility, holding particular value in regions like Jordan where drone usage is strictly restricted. However, the method also has certain limitations: its coverage is relatively limited, making it suitable for recording individual sites; it is significantly constrained by meteorological conditions, requiring stable wind conditions; the shooting process relies on the operator's experience, with room for improvement in automation; and post-processing requires manual intervention to ensure image quality. This research provides a practical technical solution for the three-dimensional recording of archaeological sites in resource-constrained areas.

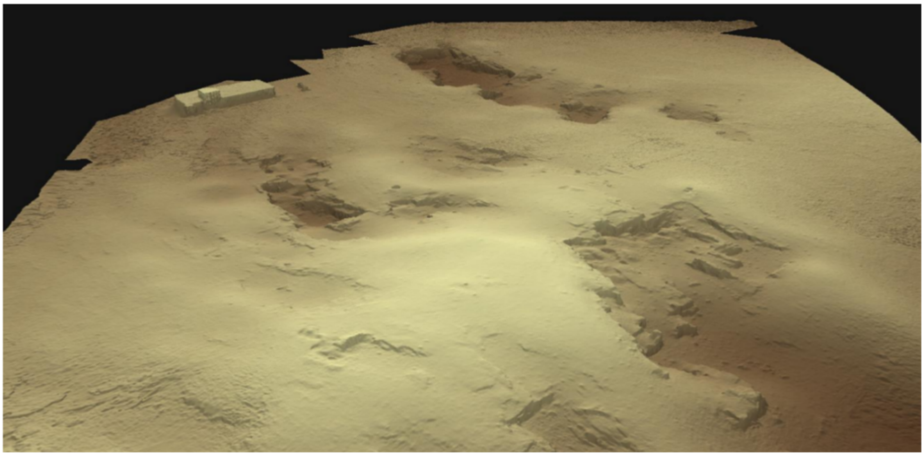

Fig. 1. A rendering of the created DEM of a part of the quarries [3].

5 Case Comparison and Insights

This paper systematically compares two case studies—Sentinel-2 imagery analysis of Serbia's Banat region and UAV-based 3D modeling of Jordan's Udhruh quarry—to reveal the complementary characteristics of satellite remote sensing and UAV remote sensing in cultural resource management.Sentinel-2 satellite imagery, with its wide coverage capability (spatial resolution of 10 meters) and multi-temporal monitoring advantages (revisit cycle of 5 days), is well-suited for large-scale site surveys and environmental dynamic monitoring. It demonstrates unique value particularly in analyzing spectral response differences during the early stages of crop growth. However, its spatial resolution has limitations in identifying small sites (less than 25 meters in diameter) and is susceptible to interference from natural topography. In contrast, UAV photogrammetry technology, utilizing low-cost platforms (such as kites equipped with consumer-grade cameras) and Structure from Motion (SfM) algorithms, enables centimeter-level precision in 3D modeling (e.g., achieving 1.1-centimeter accuracy in the case study). This makes it particularly suitable for detailed documentation of sites in complex terrain.

The two technologies are not in competition but form a multiscale collaborative framework spanning from macro to micro levels. Satellite remote sensing excels at regional-scale site screening and long-term monitoring, while drone technology focuses on detailed modeling and conservation planning for individual sites. This complementarity necessitates that cultural resource management employ technologically appropriate solutions tailored to specific objectives, environmental characteristics, and resource conditions. For instance, in resource-constrained areas such as Jordan's desert regions, low-cost drone solutions demonstrate significant practical value; conversely, for large-scale heritage corridor monitoring—such as along the Silk Road—the multi-temporal analysis capabilities of satellite remote sensing prove more critical.

Future research must transcend the limitations of single-technology applications by advancing the standardized integration of multi-source remote sensing data (satellite, UAV, LiDAR) and machine learning-assisted interpretation. Particular emphasis should be placed on establishing long-term monitoring mechanisms and data-sharing protocols to facilitate a shift from reactive restoration to proactive conservation. Concurrently, efforts should strengthen the alignment between remote sensing outcomes and management practices, developing actionable technical guidelines to promote the scientific and intelligent advancement of cultural heritage preservation.

6 Conclusion

This study systematically explores the application of remote sensing technology in cultural resource management. Through a combination of theoretical analysis and empirical research, it thoroughly elucidates the comprehensive value and practical pathways of multi-source remote sensing data in cultural heritage conservation. Through systematic analysis of the synergistic application of satellite remote sensing and unmanned aerial vehicle (UAV) technology in cultural resource management, a significant complementary relationship has been demonstrated between multi-scale remote sensing techniques. Sentinel-2 satellites excel at macro-scale site surveys and environmental monitoring, while UAV technology focuses on detailed modeling of micro-scale sites. Together, they form a complete technical chain from discovery to documentation, and their selection should be based on a comprehensive assessment of specific management needs, environmental characteristics, and resource conditions.

Future research may explore the following avenues: First, expand the scope of studies to encompass a wider range of environmental types and cultural contexts. Second, enhance the development of multi-source data fusion technologies and establish standardized data processing workflows. Third, promote the deep integration of technological innovation and management practices to develop intelligent cultural heritage protection systems tailored to practical needs.

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