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Remote Sensing and GIS for Archaeological Landscape Assessment and Heritage Conservation in Libya

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الاستشعار عن بُعد ونظم المعلومات الجغرافية لتقييم المشهد الأثري والحفاظ على التراث في ليبيا

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Abstract:
Libya is characterized by a wide range of unique natural environments with a great variety of ancient archaeological sites of immense cultural value. However, these sites are under threat from urbanization, agricultural expansion, coastal activities, erosion processes, and anthropogenic activities like looting. This study utilized a combination of remote sensing and geographic information system (GIS) tools in the identification of archaeological sites and the assessment of the conservation status of 8 distinct archaeological landscape covers in Libya: Cyrene, Leptis Magna, Sabratha, Ghadames, Tadrart Acacus, Ghirza, Ptolemais, and Haua Fteah Cave. The study used Google Earth Engine API to process the images and perform analysis, with Landsat and Sentinel-2 multispectral satellite imagery serving as the main data sources. The true-color (B4-B3-B2), false-color (B8-B4-B3), PCA, and NDVI/NDMI composites were used in the characterization of the study area and the identification of anomalies. Additionally, the study analyzed Sentinel-1 VV/VH data to identify changes in surface roughness, moisture, and structure, while the digital elevation model (DEM) was utilized to analyze the relationship between the geomorphology of the study area and archaeological sites. Comparison of historical Landsat and recent Sentinel-2 Landsat imagery enabled the identification of human-driven processes such as urbanization and agricultural expansion as well as natural processes such as vegetation changes and surface erosion. Following the characterization and analysis process, a GIS-based archaeological conservation risk assessment was performed and a four-class archaeological risk classification map was generated with the following classes: low, moderate, high, and very high-risk zones. This study establishes the link between the application of remote sensing technologies and archaeological site conservation while demonstrating its potential to support large-scale archaeological landscape cover mapping and analysis at the country level.

Keywords: Archaeological Heritage, Conservation Risk, Remote sensing, GIS, Libya.

الملخص

تتميز ليبيا بتنوع واسع في البيئات الطبيعية الفريدة، وتزخر بالعديد من المواقع الأثرية القديمة ذات القيمة الثقافية الهائلة. ومع ذلك، تواجه هذه المواقع تهديدات ناجمة عن التوسع العمراني، والتوسع الزراعي، والأنشطة الساحلية، وعمليات التعرية، بالإضافة إلى الأنشطة البشرية الضارة مثل أعمال النهب. استخدمت هذه الدراسة مزيجاً من تقنيات الاستشعار عن بُعد ونظم المعلومات الجغرافية لتحديد المواقع الأثرية وتقييم حالة الحفاظ عليها في ثمانية مواقع أثرية متميزة في ليبيا، وهي: قورينا (شحات)، ولبدة الكبرى، وصبراتة، وغدامس، وتدرارت أكاكوس، وغيرزة، وبطلميس، وكهف هواء فتيح. اعتمدت الدراسة على منصة واجهة برمجة تطبيقات لمعالجة الصور وإجراء التحليلات، مستعينةً بصور الأقمار الصناعية متعددة الأطياف من نظامي لاندسات وسنتينل-2 كمصادر رئيسية للبيانات. كما استُخدمت تقنيات الألوان الحقيقية، والألوان الزائفة، وتحليل المكونات الرئيسية، ومؤشرات الغطاء النباتي والمياه لتوصيف منطقة الدراسة ورصد أي تغيرات أو شذوذات. وبالإضافة إلى ذلك، جرى تحليل بيانات سنتينل-1 بنمطي للكشف عن التغيرات في خشونة السطح، والرطوبة، والبنية، بينما استُخدم نموذج الارتفاع الرقمي لتحليل العلاقة بين التضاريس والمواقع الأثرية. ومن خلال مقارنة صور "لاندسات" التاريخية بصور "سنتينل-2" الحديثة، أمكن رصد العمليات الناتجة عن التدخل البشري -كالتوسع العمراني والزراعي- إلى جانب العمليات الطبيعية، مثل تغيرات الغطاء النباتي والتعرية السطحية. وفي أعقاب عمليات التوصيف والتحليل، أُجري تقييم لمخاطر الحفاظ على المواقع الأثرية باستخدام نظم المعلومات الجغرافية، مما أسفر عن إعداد خريطة تصنيفية للمخاطر الأثرية تتضمن أربع فئات: مناطق ذات مخاطر منخفضة، ومتوسطة، وعالية، وعالية جداً. وتُرسّخ هذه الدراسة الرابط بين توظيف تقنيات الاستشعار عن بُعد والحفاظ على المواقع الأثرية، كما تُبرز إمكانات هذه التقنيات في دعم عمليات المسح والتحليل واسعة النطاق للمواقع الأثرية على مستوى البلاد.

الكلمات المفتاحية: التراث الأثري، مخاطر الحفاظ، الاستشعار عن بعد، نظم المعلومات الجغرافية، ليبيا.

Introduction

According to Archiqoo (2017) there are 63 archaeological sites in Libya. Historical sites, heritage sites, and monuments are the types of Libyan archaeological sites. Its archaeological legacy includes ancient Greek and Roman cities along the Mediterranean coast, ancient Islamic communities in the interior, and prehistoric rock-art landscapes in the Sahara. The archaeological locations in Cyrene, Leptis Magna, Sabratha, Ghadames, and Tadrart Acacus are five Libyan cultural holdings that are now listed on the UNESCO World Heritage List (UNESCO World Heritage Centre, 2016). The archaeological landscapes of Libya are extensive and varied. Coastal archaeological sites are threatened by urbanization, agriculture, coastal processes, erosion and infrastructure developments, while desert archaeological sites are affected by aeolian erosion, sand intrusion, off-road vehicle tracks and the challenge of restricted access. However, UNESCO World Heritage Centre (2016) has recorded a number of conservation problems affecting Libya's World Heritage properties and stressed the need to systematically document the damage and monitor the condition of its sites.

Fig. 1 represents the national spatial framework for the archaeological assessment, with the distribution pattern of selected archaeological heritage sites identified. The figure indicates the general location of the five UNESCO world cultural and natural heritage sites, including Cyrene, Leptis Magna, Sabratha, Ghadames, and Tadrart Acacus. It also shows the range of environments from Mediterranean within the coastal zone and semi-arid inland areas to the Saharan regions. Notably, Ghirza, Ptolemais, and Haua Cave are additional sites that extend the distribution pattern of the identified archaeological landscapes. Thus, from the figure, it is evident that there is a wide range of variations between coastal archaeological sites versus inland or desert archaeological sites.



Fig. 1: Location and archaeological heritage map of Libya.

Traditional archaeology is usually very informative but sometimes challenging, time consuming and costly. It can be difficult to get results over a large survey area. A satellite-based remote sensing approach can offer a solution that can repeatedly monitor archaeological sites and landscape from a much larger scale than previous methods (Banerjee and Srivastava, 2013; Tapete and Cigna, 2017; Bachagha et al., 2020; Waagen, 2025). There is a considerable, albeit still limited, amount of archaeological research in Libya that has made significant contributions to the field. This research has utilized a variety of satellite image analysis tools, remote sensing, GIS, and change detection methods. The literature searched for by the author progressed from initial studies using Landsat to analyses employing high-resolution multispectral sensors, synthetic aperture radar, Google Earth Engine, and machine learning algorithms for cultural heritage surveillance. Allan and Richards (1983) were the first to assess the archaeological significance of utilizing satellite images for mapping in Libya. They suggested that it might be a good way to examine archaeological sites extensively while also obtaining information about the characteristics of the terrain. The study attempted to combine satellite imagery with analyses of the land and its assessment. It aimed to provide improved methods for archaeological surveying while also explaining how the distribution and height of ancient settlements might differ on various types of land in Libya. It can be stated that this research was one of the first to utilize satellite imagery for archaeological landscape studies in Libya and provided the necessary background for further studies, including Landsat-related archaeological and environmental surveys. D'Urso et al. (2015) attempted to study the case of coastal protection of Sabratha and Leptis Magna (Libya), which were both at risk of coastal erosion, wave action, and flooding that threatened the archaeological sites. For example, the erosion of the sandstone coast of Sabratha resulted in the sea engulfing Roman ruins. Leptis Magna's coastal retreat and multiple floodings of the Wadi Lebda also posed a danger to the archaeological site. The authors used a combination of satellite images and digital terrain modelling (DTM), comprehensive bathymetric surveys, multi-beam measurements, and ground investigations to reconstruct the coastal and river morphologies. The obtained data was compiled into a spatial information system that allowed designing coastal protection structures and rehabilitating the Wadi Lebda's hydrology. The study therefore proved the effectiveness of using remote sensing and GIS data combined with field surveys for studying coastal changes in Libya. Saad et al. (2016) examined the chora (rural territory) of Cyrene in northeastern Libya, specifically the region between Cyrene and El-Gubba/Qubbah, using an approach that combined GIS and archaeological survey. The researchers integrated field survey and excavation, differential GPS, intensive use of high-resolution satellite and remote sensing data, geomorphological reconstruction, laser scanning, geophysical survey, and detailed mapping of archaeological features. This information was then synthesized in a multilayer GIS database, enabling the reconstruction of individual rural sites poorly known before and an assessment

of their relation to the wider landscape. Of particular interest were the Late Antique fortifications and Christian basilicas; the distribution patterns of rural settlement sites, walled enclosures, roads, and agricultural estates were also analyzed. The study highlighted the potential of using satellite remote sensing in combination with traditional archaeological survey and GIS for studying and recording the extensive but relatively understudied archaeological landscape of Libya. Al Raeid et al. (2016) conducted their research about the Cyrene necropolis in the eastern part of the northern Africa. It is one of the biggest cemetery complexes in the Mediterranean region. The scientists mainly explored its eastern and southern parts by applying GIS-based archaeological inventory, differential GPS, robotic total-station surveying, and high-resolution multispectral satellite imagery. In addition, they used historical maps, RADAR data, DEM, and DTMs. Over 2000 tombs were recorded and mapped during the research. After that, the scientists-initiated monitoring of changes in the necropolis with the help of remote sensing and Google Earth. They also pointed out the damage done to archaeological objects due to unplanned urbanization, modern construction, looting, and vandalism. The study proved that it is possible to make a proper inventory of the vast necropolis and monitor its changes with the help of satellite imagery, GIS technologies, and field surveys. Rayne et al. (2017) attempted to assess the state of the archaeological heritage of Libya using remote sensing, interpretation of satellite images, field survey, aerial mapping, and available archaeological resources. The researchers utilized four regions as the basis for their assessment: the coastal plain around Zliten, Wadi Sofeggin in the pre-desert, and the desert oases of Jufra and Murzuq. The study revealed that the country's archaeological sites are under threat from agriculture intensification, urbanization, extractive industries, theft, vandalism, armed conflicts, and natural forces. Notably, the researchers emphasize the value of satellite imagery, including historical Landsat images, in documenting and delineating archaeological sites and the impact of anthropogenic activities such as agriculture and urban expansion on them. The study concludes by arguing that the remote sensing technique is an effective approach to monitor and record the heritage values of archaeological sites in Libya. Rayne et al. (2020) conducted a study to assess archaeological-site change in the Jufra oases in central Libya (Sukna, Hun, and Waddan) using the publicly available Sentinel-2 satellite sensor and Google Earth Engine. Eighty-two archaeological sites were analyzed using an automated pixel-based change detection approach to examine recent changes in archaeological sites. The authors found that agricultural intensification, field levelling, tree planting, trackway creation, and runoff had impacted many ancient sites, including severe damage to ancient foggaras. An overall accuracy of 91% was achieved for the Jufra case, proving that free and publicly available satellite pictures can be used to create an effective but accessible method for large-scale archaeological site monitoring. The analysis did not detect a few minor changes, proving that satellite imagery should only be used in combination with traditional field surveys. Buzaian et al. (2025) assessed the effect of rapid urbanization on archaeological heritage in the area of Lefakat south of Benghazi, Libya. The EAMENA machine learning automated change detection (MLACD) method and field surveys were applied to identify changes over 2019–2024. The changes were detected by analyzing Sentinel-2 satellite images using a supervised Random Forest classification in order to distinguish bare, urbanized, and vegetated surfaces. The remote-sensing analysis coupled with fieldwork revealed 30 archaeological sites, most of which dated back to the Roman period. The authors concluded that the primary threat to archaeological heritage in the research area was represented by urbanization and vegetation advance. Moreover, the field survey allowed the researchers to identify additional threats, including unauthorized excavation, rubbish dumping, bulldozing, and reuse of archaeological sites. The study proved that satellite-based change detection could be used for rapid archaeological site monitoring, but such analyses should be supported by fieldwork to document both remotely sensed changes and the in-situ threats not identified by satellite sensors.

Representative archeological regions around Libya are covered in this study, with a focus on: (1) Cyrene (northeastern Libya); (2) Leptis Magna (northwestern Libya); (3) Sabratha (northwestern Libya); (4) Ghadames (western Libya); (5) Tadrart Acacus (southwestern Libya); (6) Ghirza (central-western Libya); (7) Ptolemais (northeastern Libya); and (8) Haua Fteah Cave (northeastern Libya). The main objective of this study is to design an integrated remote sensing and GIS-based framework for assessing archaeological landscapes, identifying potential archaeology, monitoring changes, and determining conservation status through potential spatial variables for the selected sites in Libya.

2. Methodology

The present study exploited an integrated remote sensing and GIS-based approach for the archaeological landscape analysis. True-color (B4-B3-B2), false-color (B8-B4-B3), PCA, and NDVI/NDMI color composite images were first extracted from the Sentinel-2 multispectral data. The derived composite images were then thematically interpreted for the identification of ground objects, vegetation, moisture, and archaeological anomalies. Similarly, the backscatter coefficient data from the Sentinel-1 VV/VH polarization SAR data were thematically classified to extract out information on surface roughness, ground moisture, and structural differences. Furthermore, the DEM data were used to derive elevation, slope, aspect models, and other hydrographic features around the archaeological sites under study. The overall results were compared using historical Landsat and recent Sentinel-2 data for the identification of both man-made and environmental changes before finalizing the results in a GIS environment. The final GIS thematic information was then used to classify the archaeological conservation risk zones with low, moderate, high, and very high-risk zones.

3. Results and Discussion

The Sentinel-2 B4–B3–B2 true-color composite (Fig. 2) was created to represent the area around the archaeological sites realistically. It can be seen that different environments can be identified on the image: the Mediterranean coastal belt, urban regions, croplands, bare ground, and vast desert areas. The coastal archaeological sites are located in more developed and diverse environments, while the Saharan sites are situated in an arid region. This difference is significant for these sites since the environment affects both their visibility and the potential threats to them. Thus, the true-color image provides the basic information needed for further analysis of the sites' environments.

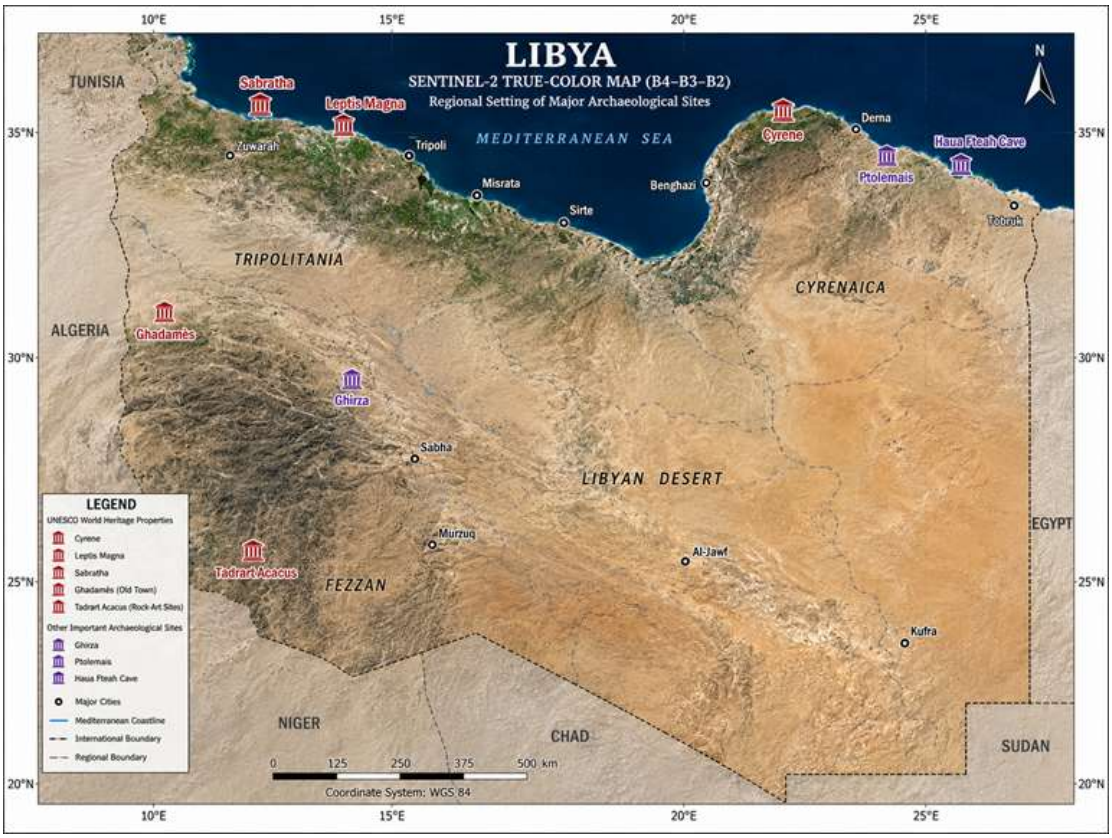


Fig. 2: Sentinel-2 true-color map of major archaeological sites in Libya.

The B8-B4-B3 false-color composite (Fig. 3) emphasizes differences between vegetated, bare, and other ground cover materials. Near-infrared reflectance is enhanced for vegetation, and differentiates bare soil, rock, man-made surfaces, and disturbed ground from healthy vegetation. This allows subtle differences in the ground cover to be seen more clearly than in the true-color image. In the vicinity of archaeological sites, these differences can sometimes be used to identify disturbed

ground, ancient land use patterns, vegetation anomalies, and exposed archaeological surfaces. The figure therefore acts as an important intermediary between general landscape interpretation and specific archaeological anomaly identification.

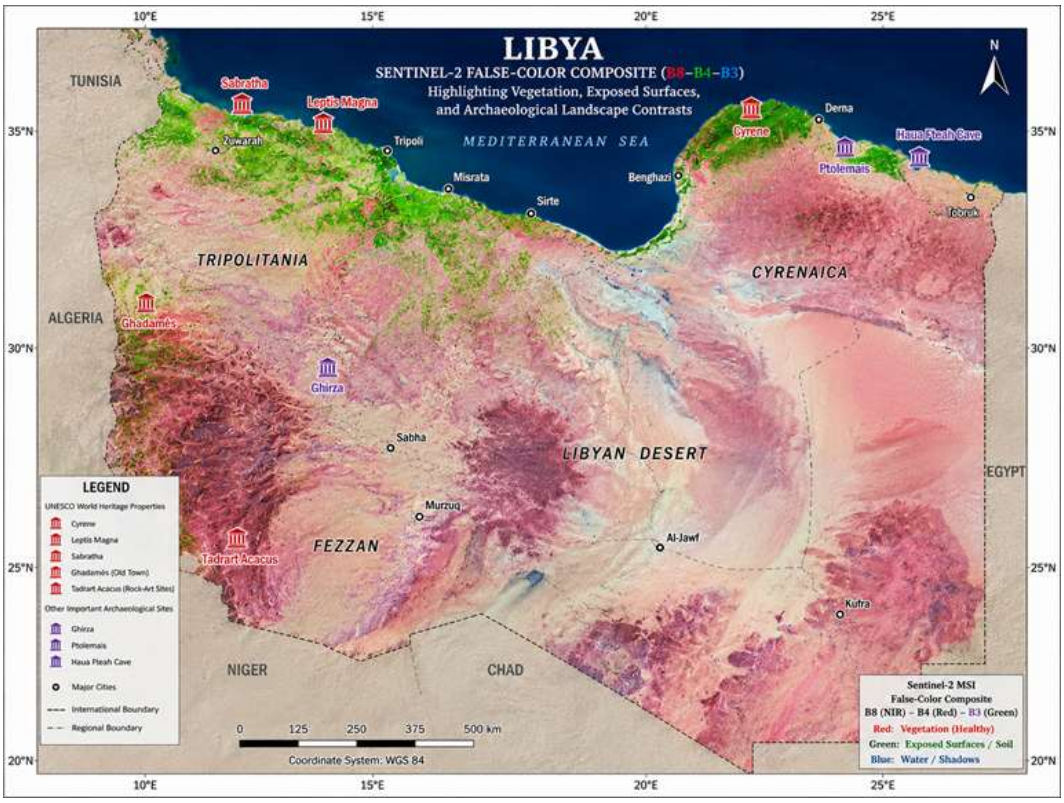


Fig. 3: Sentinel-2 false-color composite of major archaeological sites in Libya.

The principal component analysis (PCA) of the archaeological-anomaly analysis (Fig. 4). The method of PCA highlights the main trends that mask the image's spectral diversity; therefore, minor variations in the pixel's spectral properties are emphasized. The observed anomalies can be associated with variations in the properties of the soil, surface materials, vegetation, moisture, bedrock, or anthropogenic activity. Localized or linearly arranged anomalies that may be found above the archaeological places are especially noteworthy. Nevertheless, the detected anomalies should not be considered as indirect evidence of the presence of ancient structures since the similar spectral characteristics can be caused by natural occurrences.



Fig. 4: PCA archaeological-anomaly map of major archaeological sites in Libya.

Fig. 5 shows the interpreted results of the landscape. The figure highlights those linear and rectangular features, as well as circular and other shapes, which might be of archaeological significance. Linear features could mark the positions of ancient roads, walls, boundaries, canals, or other structures. Similarly, rectangular and orthogonal features could be the remnants of foundations, compounds, field systems, or other anthropogenic structures, whereas circular features could be enclosures, tombs, mounds, and other structures of different types. The potential significance of individual features is higher if they form consistent patterns, groups, or clusters, as well as when they coincide with anomalous areas identified in the PCA, NDMI/NDVI, SAR, or DEM plots. Generally, the figure summarizes anomalous points found in the analyses above and provides specific leads for possible archaeological research.

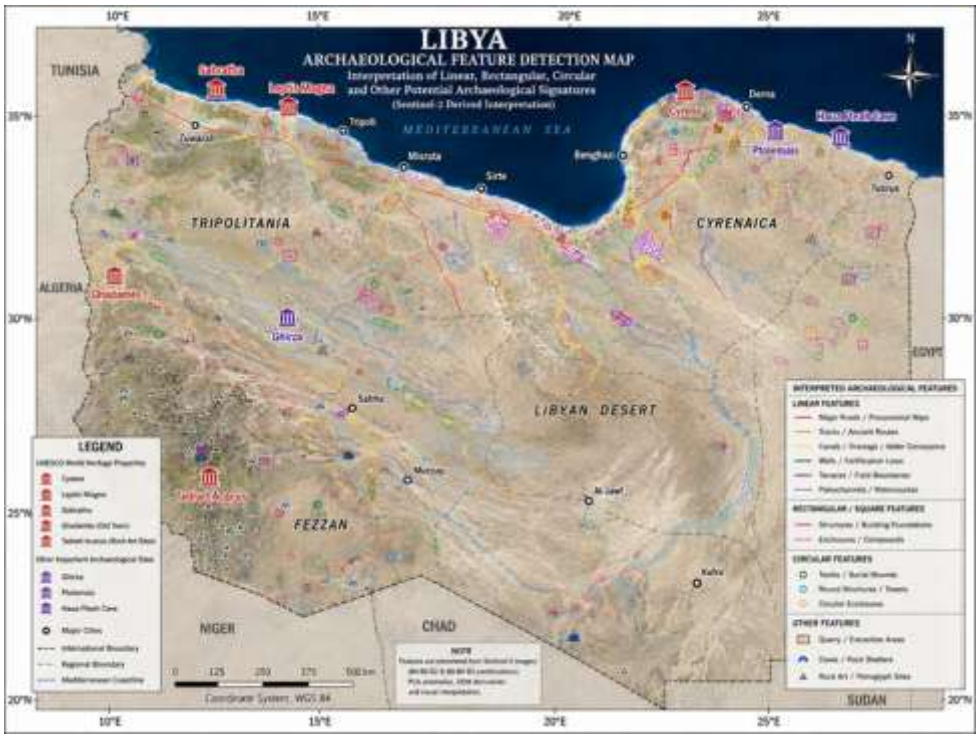


Fig. 5: Archaeological feature detection map of major archaeological sites in Libya.

Fig. 6 displays the vegetation and moisture peculiarities based on the NDVI and NDMI data. The vegetation can be affected by the presence of buried archaeological formations due to changes in the amount of topsoil, its drainage ability, moisture content, and vegetation density. The similar effects can be caused by the variations in the local moisture conditions or characteristics of the underlying sediments. As a result, such changes in the environment can be revealed as anomalies of vegetation or moisture. For example, there are visible in the figure areas with different vegetation development, which can be caused by the different conditions of the topsoil. On the other hand, the map can also show the zones of environmental degradation, vegetation loss, dryness, and other processes that can threaten the archaeological heritage. Therefore, this figure can be used for both archaeological prospecting and environmental monitoring purposes.

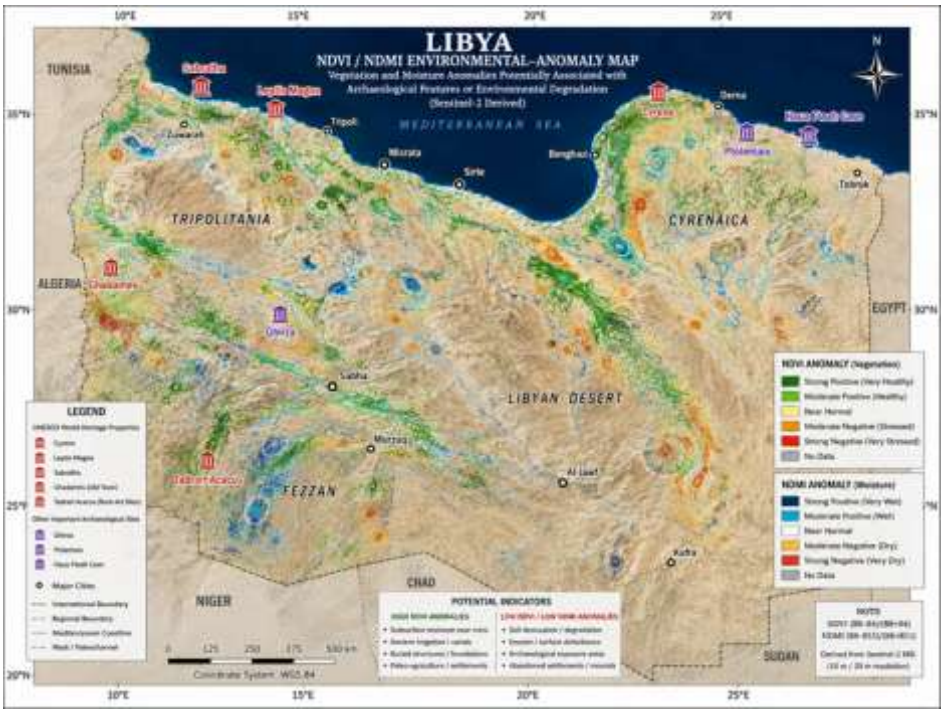


Fig. 6: NDVI/NDMI environmental-anomaly map of major archaeological sites in Libya.

Fig. 7 provides additional information based on Sentinel-1 VV/VH SAR backscatter. Radar fundamentally differs from visible and infrared light, as it is reflected by different types of surface roughness, moisture, vegetation structure, and material. As a result, anomalies in these parameters can become visible in the SAR imagery, which may not be apparent in the optical images. In particular, significant or unusual backscatter variations can be caused by the presence of manmade structures, rough archaeological surface, disturbance of the ground surface, differences in moisture, or linear objects. Additionally, anomalies in SAR data can complement and explain anomalies found in optical imagery since an anomaly that was detected in both datasets is more likely to represent a significant change than one that was found in only one type of imagery.

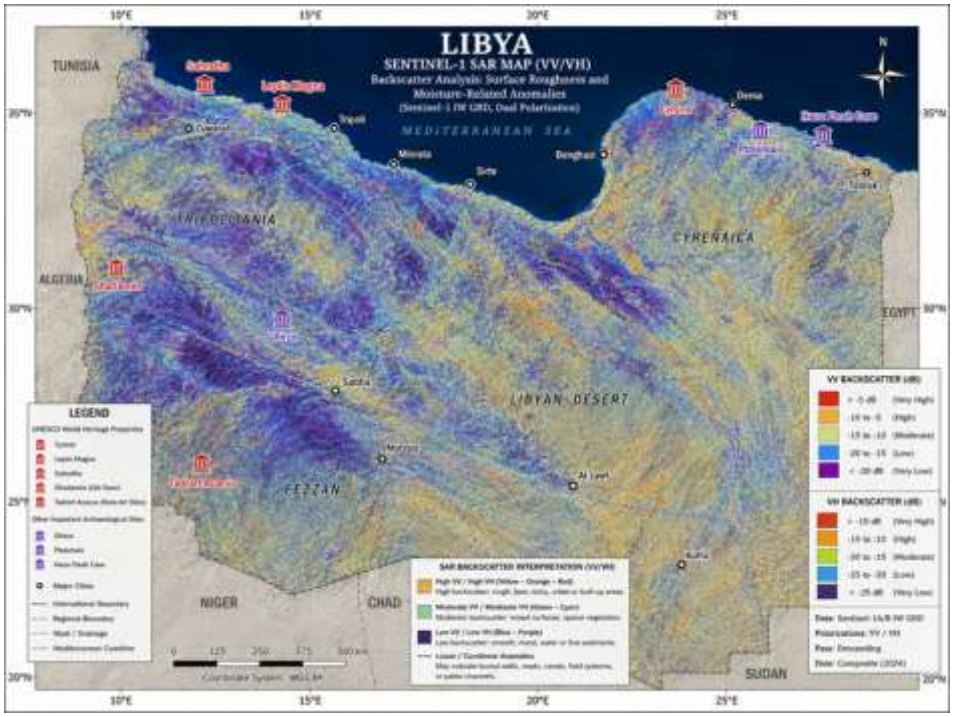


Fig. 7: Sentinel-1 SAR map of major archaeological sites in Libya.

Fig. 8 depicts the topographical and geomorphological features of the archaeological sites under study, using the plot of elevation, hillshade, slope, drainage, and terrain morphology. This data can help determine whether archaeological sites are located in valleys, on hill crests and terraces, along drainage ways, on slopes, or on flat areas. Terrain morphology is directly related to the access to water, the availability of flat places for settlements and their locations relative to transportation routes. Moreover, this type of data can help identify the relationship between archaeological sites and ancient water sources and explain the distribution patterns of these sites reflected in the optical, PCA, and SAR data sets. Thus, the DEM data can provide a geological explanation for the patterns found in the previous analyses.

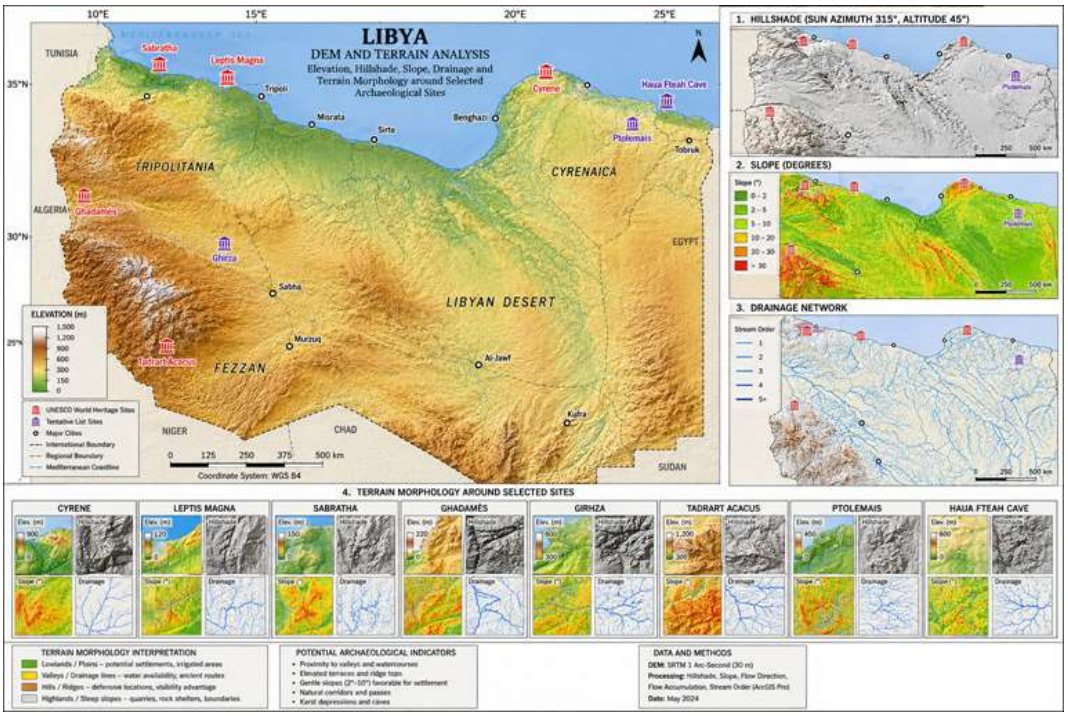


Fig. 8: DEM and terrain analysis of major archaeological sites in Libya.

Fig. 9 presents an assessment of the changes in the archaeological landscape through time using the historical Landsat and the latest Sentinel-2 satellite imagery. Such an analysis helps understand the trends in the development of the region, urbanization processes, agricultural land use, changes in vegetation indices, surface disturbances, and environmental degradation. It is especially important to assess coastal archaeological sites because they are frequently surrounded by areas subject to accelerated anthropogenic development, unlike the sites in the desert that face other threats. In this case, the historical images can serve as an excellent reference for the current state of the archaeological sites to define if any specific changes occurred in the region. Therefore, the change detection analysis can be helpful to prioritize the sites or buffer areas around them for further detailed analysis.



Fig. 9: Multi-temporal change detection of major archaeological sites in Libya.

Fig. 10 depicts the final integrated conservation evaluation, which summarizes the previous remote-sensing and GIS analyses in terms of four levels of potential risk: low, moderate, high, and very high. Generally, the resulting map indicates the approximate spatial distribution of sites of potential archaeological heritage significance that could be subjected to various environmental and human-related impacts. Of these, the high- and very-high categories require further on-site survey, inspection, investigation, and conservation. The lower categories are not of great concern in terms of immediate impact but may necessitate further closer inspection. The value of this figure is that it shifts the focus of archaeological heritage research from simple discovery to conservation management: it helps to focus conservation-related efforts on the most pressing sites as far as environmental impact is concerned.

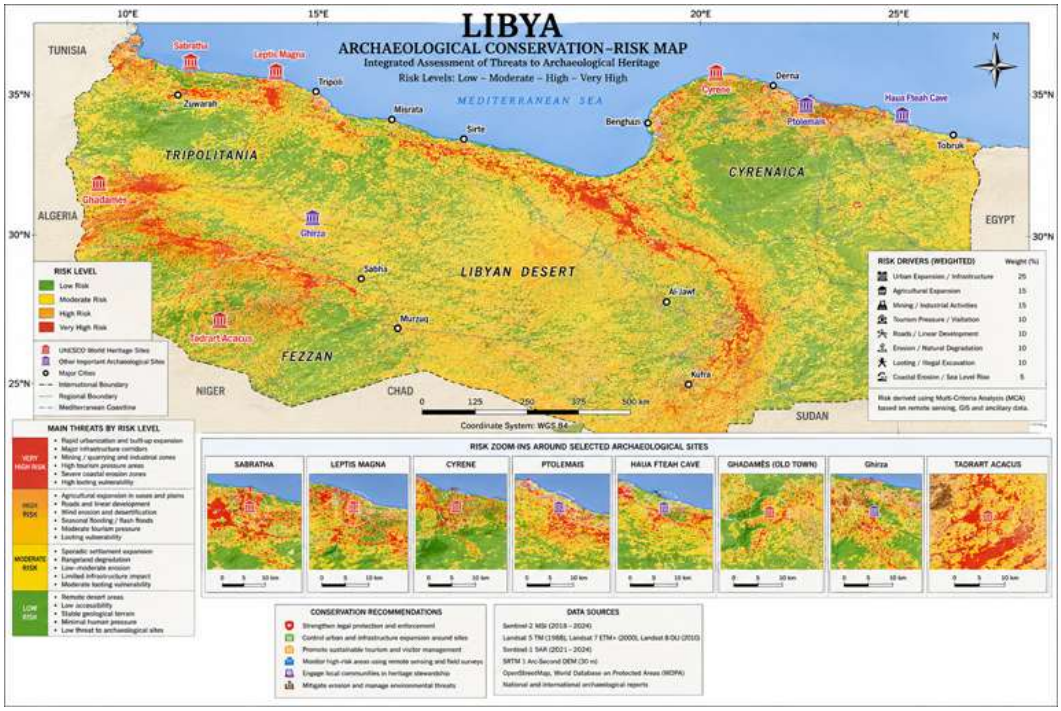


Fig. 10: Archaeological conservation-risk map of major archaeological sites in Libya.

4. Conclusions and Recommendations

This study illustrated the effectiveness of the combined use of multi-source remote sensing and GIS for archaeological landscape assessment in Libya. The analysis using Sentinel-2 data proved effective in terms of distinguishing major landscape classes, as well as identifying vegetated, bare-rock, bare-soil, and disturbed areas. The use of false-color composition facilitated the visual identification of landscape types, while the spectral complexity of PCA allowed detecting subtle spectral anomalies related to possible archaeological or anthropogenic features. At the same time, spectral anomalies of natural origin, whether related to geology or biology, should not be ignored, which means that not all of them should be necessarily considered archaeological indicators. The analysis of archaeological feature detection showed that the linear, rectangular, circular, and other patterns found could be related to roads, walls, boundaries, canals, foundations, enclosures, field systems, tombs, and mounds. The value of the detected patterns is further determined by their possible combination with other anomalies, as well as by the coincidence with the results of PCA, NDVI/NDMI clustering, SAR analysis, and DEM processing. The analysis of vegetation clustering using the NDVI and NDMI indices showed that some types of vegetation or differences in the moisture content can be valuable indicators of archaeology and environmental status. Similarly, the analysis of Sentinel-1 SAR data demonstrated the possibility of using this type of data for the assessment of the roughness of the surface, its moisture content, vegetation cover, and possible differences in man-made structures. The processing of DTM data has confirmed the importance of slope and morphology-related information, which is critical for analyzing processes associated with slopes, as well as determining potential points or areas of water accumulation and their impact on archaeology. The combined analysis of historical Landsat data with the current Sentinel-2 data proved to be a valuable approach to monitor urbanization, agricultural development, and vegetation dynamics, as well as to assess surface disturbances and impacts on the natural environment. This is especially important for coastal archaeological sites, which are subject to greater anthropogenic pressure, while desert ones are more vulnerable to desertification processes. In addition, using the remote sensing and GIS data, it was possible to determine the degree of risk to archaeological sites with the help of a four-level classification. As a result, low, moderate, high, and very high-risk sites were identified, which need different degrees of urgent attention, verification, and protection. In this light, this study has contributed to the understanding of the archaeological use of remote sensing data, since it goes beyond descriptive discoveries and focuses on the issues of monitoring and protection.

The proposed recommendations are given below:

(1) Field confirmation of the anomalies detected using Sentinel-2, PCA, NDVI/NDMI, SAR, and DEM before accepting them as archaeological sites.
(2) Starting a satellite-monitoring program that will use historical Landsat and recent Sentinel-2 to monitor changes around archaeological sites.
(3) Recommendation to utilize Sentinel-1 SAR in combination with optical imagery since the former has the potential to capture additional information about the ground surface.
(4) Creating GIS-based archaeological databases for the sites identified using the available resources, including satellite imagery, archaeological inventory, historical cartography, DEM, field surveys, and conservation data.
(5) Recommending high and very-high-risk sites for field documentation, inspection, protection, and conservation due to their potential threat level.
(6) Monitoring the growth patterns of human structures around coastal and inland archaeological sites, especially those under conservation.
(7) Using multi-temporal imagery to capture archaeological baselines or references that will be used to document changes in the future.
(8) Recommending a combination of remote sensing and conventional archaeological field surveys. Although the former has proven efficient in large-scale regional monitoring, there are minor details that may only be captured by conventional methods. The studies conducted in Libya discussed in this paper equally show the need to combine the two methods.
(9) Designing a national archaeological remote-sensing monitoring framework for Libya that will use standardized procedures, including Sentinel-1, 2, Landsat, DEM, GIS, and change detection, to monitor and assess archaeological and heritage sites.

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