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INNOVATIVE METHODS FOR SAFEGUARDING CULTURAL HERITAGE

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EXTENDED ABSTRACT

Una delle conseguenze più significative dei cambiamenti climatici è la minaccia che essi rappresentano per i siti del patrimonio culturale. Il progetto TRIQUETRA dell'UE Horizon Europe affronta questa sfida critica applicando un quadro di valutazione del rischio completo, che integra tecnologie tradizionali e avanzate, come il telerilevamento e il crowdsourcing, per quantificare la gravità del rischio, monitorare i cambiamenti nel tempo e informare strategie di mitigazione efficaci. Il rischio climatico deriva dalla combinazione di pericoli climatici, esposizione e vulnerabilità. Comprendere i rischi a livello dei singoli siti è essenziale per attuare misure di adattamento e mitigazione adeguate. Gli impatti combinati di pericoli naturali e geologici indotti dal clima, come erosione, alluvioni, frane e terremoti, minacciano l'integrità fisica dei monumenti e dei sistemi socio-economici che supportano.

La valutazione dei potenziali rischi a livello dei siti è fondamentale per ideare e attuare strategie di adattamento e mitigazione robuste. Tecniche come il telerilevamento, il radar ad apertura sintetica (SAR), le rilevazioni geodetiche, i veicoli aerei senza pilota (UAV), le simulazioni di *digital twin* e le osservazioni *crowdsourced* migliorano sia la copertura spaziale che la risoluzione del monitoraggio del patrimonio. Questi approcci integrati consentono di individuare precocemente piccoli spostamenti, deterioramenti dei materiali e *geohazards* in evoluzione, fornendo così a gestori del patrimonio e decisori politici informazioni utili per interventi di conservazione mirati. Consolidando questi flussi di dati spaziali, spettrali e strutturali, la tecnologia del *digital twin* crea repliche virtuali dinamiche dei siti del patrimonio, permettendo di simulare scenari in tempo quasi reale. Attraverso il monitoraggio ambientale continuo e algoritmi predittivi, gli esperti possono simulare virtualmente le sollecitazioni ambientali sui monumenti in condizioni estreme, come forti piogge o terremoti moderati. Questa capacità predittiva è fondamentale per spostare le pratiche di conservazione da misure reattive, spesso attivate da danni improvvisi, a un approccio proattivo che anticipa i punti deboli e ottimizza la pianificazione della manutenzione.

Anche il coinvolgimento dei cittadini è parte integrante del progetto TRIQUETRA, che presenta una piattaforma web e mobile dinamica che incoraggia i visitatori a partecipare attivamente al monitoraggio dei siti del patrimonio culturale. Attraverso l'app TRIQUETRA, cittadini e visitatori possono catturare e caricare fotografie, contribuendo con dataset preziosi che integrano e migliorano i modelli 3D esistenti. Questo processo è supportato da un sistema di backend che aiuta le autorità dei siti culturali a monitorare meglio le condizioni attraverso immagini aggiornate e segnalazioni dei visitatori. Allo stesso tempo, l'app di coinvolgimento civico TRIQUETRA crea un'esperienza più interattiva offrendo funzionalità di Realtà Aumentata (AR) immersive. Questi componenti AR forniscono informazioni aggiuntive su caratteristiche critiche a rischio, come aree colpite dai cambiamenti climatici o vulnerabilità strutturali, promuovendo la consapevolezza e gli sforzi di conservazione.

Uno degli studi di caso del progetto TRIQUETRA riguarda il sito patrimonio mondiale dell'UNESCO di Choirokoitia, uno dei siti neolitici meglio conservati nel Mediterraneo. Rappresenta il Neolitico Aceramico di Cipro al suo apice, intorno all'inizio del IX millennio. Il sito si trova nel Distretto di Larnaka, a circa sei chilometri dalla costa meridionale di Cipro. Nell'ambito del progetto TRIQUETRA, è stato esaminato il potenziale rischio di cadute rocciose a Choirokoitia, considerando che la topografia del sito è vulnerabile a movimenti causati da eventi climatici estremi e da stressori quotidiani e stagionali. La metodologia utilizzata sul sito di Choirokoitia ha dimostrato come il telerilevamento, la raccolta di dati geospaziali, la fotogrammetria, i *digital twin* e i dati *crowdsourced* abbiano contribuito collettivamente a identificare i rischi legati al clima.

La convergenza di telerilevamento, modellazione digitale, rilievi geodetici e citizen science rappresenta un cambiamento potente nei paradigmi della conservazione del patrimonio. Attraverso la cattura di dati ad alta risoluzione su più scale e la loro integrazione in modelli predittivi, gli stakeholder acquisiscono la capacità di anticipare i rischi, prioritizzare gli interventi e promuovere una gestione inclusiva. Integrando tecnologie all'avanguardia con il monitoraggio guidato dalla comunità, TRIQUETRA garantisce un approccio olistico alla salvaguardia del patrimonio culturale. Il progetto crea un quadro replicabile che migliora la valutazione del rischio, promuovendo al contempo la partecipazione attiva negli sforzi di conservazione, offrendo infine benefici scalabili per i siti del patrimonio culturale a livello globale.

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ABSTRACT

Cultural heritage sites constitute irreplaceable records of human history, illustrating the progression of our social, architectural, and cultural practices. Increasing threats from climate-related hazards, such as shifting rainfall patterns, escalating temperatures, and intensified extreme weather, combined with geological and physical risks like landslides, earthquakes, and erosion, render these sites increasingly vulnerable. Earth observation technology is pivotal in preserving cultural heritage by improving documentation, enabling more effective monitoring, and supporting proactive conservation strategies. Recently, with advances in technology, advanced 3D scanning and imaging techniques, such as laser scanning and photogrammetry, have captured precise digital records of cultural heritage sites, documenting and helping conservators measure changes over time and swiftly identify structural vulnerabilities. Remote sensing technologies, including satellite imagery, aerial photography and UAV-based surveys, allow for extensive site evaluations, reducing risks and costs associated with onsite inspections, especially in remote or hazardous locations. Methodological frameworks and technological developments, encompassing remote sensing, satellite and aerial imaging, digital modeling with laser scanners, photogrammetry, and participatory data collection, are creating fresh opportunities for proactive, evidence-based conservation. Data-driven tools such as sensor arrays and digital twin models enable continuous monitoring, where real-time structural and environmental information is integrated into predictive models to anticipate emerging threats.

This paper provides a comprehensive review of innovative remote sensing methods for safeguarding and monitoring cultural heritage under these compounded vulnerabilities. It focuses on integrating techniques employing remote sensing, geodetic methodologies, synthetic aperture radar, unmanned aerial vehicles (UAVs), digital twin platforms, and participatory data collection initiatives with sensors and crowdsourcing. A key emphasis of this study is the integration of state-of-the-art techniques for monitoring cultural heritage assets.

Examples of various studies conducted in Cyprus, more specifically the case study of the Neolithic UNESCO World Heritage Site of Choirokoitia, demonstrate the practical application of these frameworks, highlighting the TRIQUETRA project (funded by the EU Horizon Europe research and innovation programme) with an innovative integration of conventional and novel methodologies for risk quantification, site monitoring, and stakeholder participation. The findings underscore the critical necessity of interdisciplinary collaboration, sustained funding mechanisms, and robust policy support to ensure the long-term preservation of cultural heritage for future generations.

Keywords: *cultural heritage, climate change, remote sensing, digital twins, crowdsourcing, virtual reality, photogrammetry*

INTRODUCTION

Cultural heritage sites embody diverse aspects of history, technology, creativity, and social structures, offering unparalleled insights into the trajectory of human development. Climate change and geological hazards increasingly threaten cultural heritage sites' structural and aesthetic integrity. Variations in temperature and precipitation patterns, compounded by events such as landslides, earthquakes, and subsidence, subject monuments and archaeological locations to stresses often beyond the predictive capacity of conventional monitoring. Traditional methods, although foundational, tend to be labor-intensive and incapable of delivering the continuous or large-scale insights required under rapidly shifting environmental conditions (Sesana *et alii*, 2018).

There is an urgent need for more innovative, cost-effective, and scalable solutions that enable continuous monitoring and timely intervention to mitigate risks (Themistocleous, 2023; Themistocleous *et alii*, 2023). As the significance of preserving these sites grows more apparent, cutting-edge technologies have become paramount for improving monitoring and conservation endeavors. Emerging methodological frameworks and technological innovations incorporating remote sensing, satellite and aerial imaging, digital modelling using laser scanners, photogrammetry, participatory data collection and other techniques and methodologies present new opportunities for providing proactive, evidence-based conservation. Data-driven tools such as sensors and digital twin models facilitate continuous monitoring, where real-time environmental and structural information is integrated into predictive models to anticipate potential threats. This transforms heritage management from a reactive process into a proactive one, enabling intervention before irreversible damage occurs. The identification and assessment of risks must consider the history of the place, the topology and geology of the site, the environmental and vegetation conditions, and all the major risks that affect the site as a result of climate change. However, most long-term vulnerability studies on cultural heritage sites do not focus on risk assessment variables (Tang *et alii*, 2016).

Remote sensing techniques, including optical imaging, lidar, and interferometric Synthetic Aperture Radar (SAR), facilitate the detection of subtle deformations and enable the precise detection of ground movement at the millimeter scale, enabling proactive intervention. This level of detail reveals hidden indications of structural stress or subsidence that often escape conventional ground-based assessments. In parallel, terrestrial geodetic tools (*e.g.*, total stations, GNSS receivers) validate and enhance satellite findings, improving the accuracy and clarity of displacement data. Unmanned aerial vehicle (UAV) photogrammetry and laser scanning further expand the coverage of satellite observations while capturing fine-scale topographical details, such as micro-fissures or subtle slope variations. The resulting high-resolution 3D models are invaluable for quantifying material loss and identifying zones prone to severe weathering or imminent instability. Digital twin technologies extend these capabilities by integrating real-time data feeds into dynamic models, while citizen-driven data-gathering initiatives strengthen surveillance efficiency and foster community engagement.

EU research initiatives address these challenges by implementing comprehensive risk assessment models to mitigate climate-driven threats to cultural heritage. The PROTHEGO project (Themistocleous *et alii*, 2016; Themistocleous *et alii*, 2018) exemplified how Earth Observation can be systematically applied to heritage sites under threat from geohazards. The TRIQUETRA project integrates traditional site assessments with cutting-edge digital platforms to evaluate hazard intensity, track material deterioration, and guide the development of effective preservation strategies, thereby underscoring the potential of unified frameworks for risk assessment and community participation (TRIQUETRA Consortium, 2022).

This paper aims to consolidate these emerging approaches into a coherent framework suitable for large-scale heritage conservation efforts. Several research papers and journal articles have propelled the synergy of remote sensing and digital technologies in cultural heritage contexts (Themistocleous & Danezis, 2019; Themistocleous, 2024).

SITE OVERVIEW

Different remote sensing techniques, including photogrammetry, UAV imagery and digital twin modelling were applied in various sites located in Cyprus, which are discussed as examples of how innovative technologies can be used to document, monitor and safeguard cultural heritage. One of the sites included in the TRIQUETRA project is the World Heritage Site of Choirokoitia in Cyprus, which was used to study the effects of climate change on cultural heritage sites.

Choirokoitia

Choirokoitia is a remarkably well-preserved Neolithic settlement in Cyprus's Larnaca district and is one of the most significant prehistoric sites in the eastern Mediterranean (Fig. 1). Dating back to the 9th millennium BCE and occupied from the 7th to the 5th millennium B.C., it represents a pivotal period in human civilization, marking the transition from nomadic hunter-gatherer societies to settled agrarian communities. The site's circular dwellings, complex social structures, and evidence of early domesticated agriculture provide an unparalleled window into the Aceramic Neolithic period. Choirokoitia is an invaluable source of information on the Neolithic period, offering insights into how early human communities in the eastern Mediterranean adapted to island environments and structured their social and economic lives. As a UNESCO World Heritage Site, Choirokoitia is of global archaeological significance, requiring rigorous conservation efforts to ensure its preservation. However, its geographical and geological context presents substantial conservation challenges due to climate-induced environmental changes.

Situated within the Maroni River valley near the Troodos Mountain range, Choirokoitia is exposed to steep, sedimentary rock formations susceptible to weathering, erosion, and slope instability. The site's proximity to active fault lines increases the risk of rockfalls, erosion, and seismic movements, while extreme seasonal climates intensify these threats. Preliminary data from the Choirokoitia site indicate that rockfall risks are

Fig. 1 - UAV images of the Choirokoitia UNESCO World Heritage Site. Left: orthophoto showing the entire site. Right: aerial image of the dwellings at the site

substantially affected by seasonal climatic patterns, particularly the interplay between prolonged heat waves and subsequent flash rainfall events, exacerbating rockfalls and structural deterioration (Themistocleous, 2024). These conditions collectively accelerate weathering processes and water-induced instabilities, posing significant challenges to the preservation of the site (Themistocleous *et alii*, 2016).

Due to these overlapping threats, Choirokoitia was chosen as a key demonstration site for the TRIQUETRA EU project, which integrates advanced remote sensing and data-fusion techniques, building on insights from PROTHEGO research (Themistocleous *et alii*, 2018; TRIQUETRA Consortium, 2022). The combined use of diverse monitoring methods, community-based data collection, and digital twin modeling at Choirokoitia exemplifies how comprehensive risk assessment can be conducted under real-world conditions.

DATA AND METHODS

Remote Sensing and SAR data

Remote sensing forms the foundational layer of modern cultural heritage monitoring. It incorporates an array of sensor technologies, including multispectral, hyperspectral, thermal infrared, LiDAR, and SAR. SAR has proven particularly effective in detecting land and structural deformations, even under challenging conditions such as cloud coverage or nighttime operation (Themistocleous & Danezis, 2019; Themistocleous *et alii*, 2018). Different studies conducted in Cyprus have used remote sensing and Earth observation for cultural heritage and archaeology to document and monitor archaeological sites, detect crop/soil marks of buried archaeological sites, produce risk assessment maps, monitor erosion in coastal archaeological areas as well as identify and monitor looting activities.

SAR data, analyzed through interferometric processing (InSAR), allows researchers to measure incremental ground movements with millimeter-scale precision. This non-contact, wide-area coverage is instrumental for mapping hazard-prone regions and identifying preliminary signs of structural stress in monuments and archaeological sites. The PROTHEGO initiative highlighted the versatility of InSAR in detecting subsidence and slope instability across different European heritage locations (Themistocleous *et alii*, 2016; Themistocleous *et alii*, 2018). By comparing multiple SAR images acquired over specific time intervals, phase differences manifest uplift, settling, or lateral displacement patterns. Post-processing workflows typically involve co-registration, topographic phase removal, filtering, and phase unwrapping. The final displacement maps can then be validated against ground control points, often derived from geodetic stations, to correct for potential atmospheric distortions. When integrated with other remote sensing data, such as optical imagery, InSAR outputs offer a robust means of pinpointing areas where targeted interventions or more refined surveys might be necessary.

SAR technology offers numerous applications in the preservation and study of cultural heritage. It can help uncover subtle terrain features or soil moisture variations that suggest where buried archaeological structures may exist. For risk assessment and structural health, particularly in regions prone to tectonic activity or excessive groundwater extraction, Interferometric SAR (InSAR) provides precise measurements of ground movement that may affect cultural heritage sites, thereby enabling conservation specialists to take preventative measures. In conflict zones, SAR's all-weather imaging capacity proves essential for remote surveillance of heritage sites threatened by illegal looting or destruction, especially when on-the-ground access is too dangerous. Additionally, SAR helps identify flood extents and monitor shoreline changes, offering invaluable insights for protecting coastal and riverine cultural landmarks at risk of erosion or inundation.

Geodetic monitoring and UAV photogrammetry

Geodetic monitoring techniques, including total stations, leveling, and GNSS, provide high-accuracy measurements crucial for cross-referencing remote sensing observations. While satellite-based methods excel in generating broad coverage, in-situ geodetic networks offer near-continuous records of vertical and horizontal displacements at the local scale (Themistocleous, Gikas, & Danezis, 2021) and is carried out by installing electrical sensors in selected structures with automatic systems for data acquisition and recording or by using portable instruments with manual reading of data taken at fixed time intervals (Zhou *et alii*, 2015; Garziera *et alii*, 2007; Glisic & Inaudi, 2008). This synergy significantly enhances the reliability of deformation analyses, enabling scholars and site managers to distinguish between genuine ground motion and potential noise artifacts or atmospheric disturbances present in satellite data.

By providing precise ground motion measurements at varying spatial and temporal resolutions, geodetic monitoring helps cultural heritage specialists identify the underlying causes of deformation. Such observations can reveal how factors like groundwater extraction, seismic activity, or soil compaction affect the structural integrity of important historical buildings and archaeological sites, allowing for timely interventions and preservation efforts. In cultural heritage areas UAV applications are mainly focused on documentation, observation, monitoring, mapping, 3D modelling and 3D reconstruction [18], as well as digital maps, digital orthophoto, digital elevation model (DEM) and digital surface models (DSM).

Unmanned Aerial Vehicle (UAV) technology has emerged as a valuable, cost-effective means of safeguarding, investigating, and disseminating cultural heritage. UAVs offer affordability, reliability, and non-invasiveness while facilitating rapid data capture compared to traditional survey methods or manned aerial photography. They can collect highly detailed imagery and spatial information from perspectives otherwise inaccessible.

UAV photogrammetry augments ground-based approaches by providing high-resolution imagery. Proper flight-path planning ensures adequate overlap between successive images, enabling specialized software to reconstruct three-dimensional surfaces as orthophotos and digital elevation models (DEMs) (Figure 2). The precision of these outputs supports accurate documentation and monitoring of changes over time. Moreover, UAV platforms are particularly advantageous for steep or remote locations where manual surveys pose logistical or safety challenges (Themistocleous, 2019).

At the Choirokoitia site, the digital twin model includes UAV-based orthophotos, LiDAR scans, geodetic station outputs, and climate variables, such as temperature, humidity, and rainfall, to monitor climatic changes that affect the site. This methodology enables a better understanding of how archaeological elements respond to long-term cumulative stresses, guiding heritage management away from reactive repairs toward a more proactive, preventative approach.

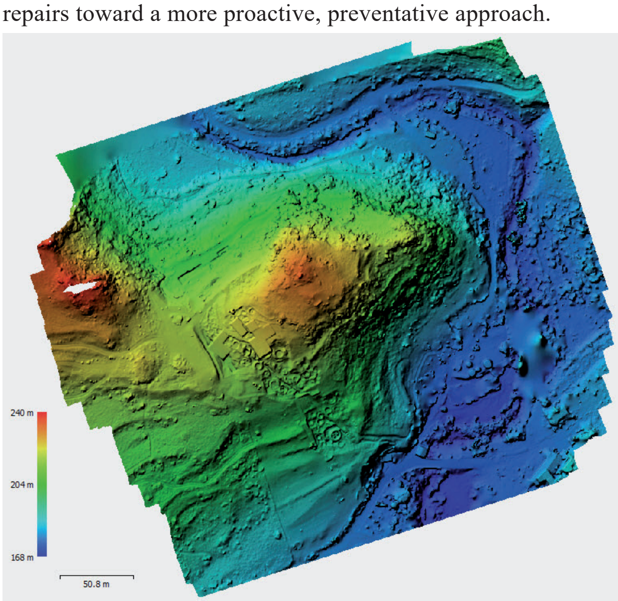

Fig. 2 - Digital Elevation Modeling (DEM) showing the topography of the Choirokoitia site

Digital twin technology

Digital twins have emerged as a powerful tool for dynamically monitoring and managing cultural heritage sites (Lu, 2021). They serve as virtual replicas of physical assets, integrating real-time data with advanced simulation models to incorporate various data types, ranging from high-resolution 3D representations and environmental data to structural health monitoring and historical documentation (Rodic & Eric, 2022). This technology allows for continuous observation of a site's condition, prediction of future changes, and timely interventions, thus supporting a proactive approach to preservation (Grieves & Vickers, 2017). By consolidating documentation, monitoring, and analysis within a single adaptable platform, digital twins address both environmental and anthropogenic threats, particularly those linked to natural hazards (Rodic & Eric, 2022; Themistocleous, 2024).

As detailed virtual replicas of physical sites, digital twins offer a transformative method of heritage conservation through real-time monitoring, predictive analysis, and comprehensive documentation (Themistocleous *et alii*, 2022; Gabriele *et alii*, 2023). They are particularly useful in settings where climate change and natural hazards pose significant risks. By enabling rapid assessments of environmental impacts, digital twins allow conservationists to anticipate emerging threats and respond effectively (Lu, 2021).

Their construction begins with high-resolution 3D modeling produced via photogrammetry using UAV-based orthophotos (Themistocleous & Abate, 2024). The data gathered from different sources, such as 3D structural scans, environmental readings, and historical records, are combined in a comprehensive digital twin, employing sophisticated simulation models to facilitate ongoing site monitoring (Themistocleous *et alii*, 2022). A key advantage is the ability to compare digital models across different time periods to identify threats from climate change, extreme weather, or other environmental and anthropogenic pressures (Fatoric & Seekamp, 2017).

Digital twins also integrate onsite sensor data to monitor environmental changes, including those driven by climate and natural hazards. Predictive models help anticipate potential effects, while regular comparative analyses detect any signs of deterioration, which allows well-informed, timely interventions. Beyond monitoring, these systems serve as comprehensive documentation platforms, merging measurements, annotations, and historical records in a dynamic, real-time representation that supports both analysis and decision-making (Themistocleous & Abate, 2024; Themistocleous, 2024).

Fundamentally, digital twin paradigms translate physical systems into data-rich virtual environments. By consolidating 3D geometry, sensor feeds, remote sensing outputs, and historical information, they create a living model of the heritage site (Themistocleous, 2024). These virtual simulations are particularly adept at evaluating "what-if" scenarios that account for climate stresses, seismic activity, and human influences. Feeding real-time environmental metrics into computational models further enables heritage stakeholders to forecast imminent hazards, test conservation methods, and assess restoration materials.

Within the TRIQUETRA EU project (TRIQUETRA Consortium, 2022), digital twins incorporate UAV-based orthophotos, LiDAR scans, geodetic station outputs, and climate variables, such as temperature, humidity, and rainfall, to perform predictive analytics, often powered by machine learning. This approach offers insights into how architectural elements respond to cumulative stresses over time, shifting heritage management from a reactive stance of repairing visible damage to a more proactive, preventive strategy.

Crowdsourcing and citizen science

The project provides a multidisciplinary approach that integrates remote sensing and monitoring through crowdsourcing to establish an effective early-warning system for site conservation (Themistocleous, 2024). Crowdsourcing and citizen science introduce public involvement to supplement expert-driven observations. These systems generate a considerable volume of real-time data by encouraging visitors to document physical anomalies at heritage sites, such as cracks, discolorations, or water ingress. Although this approach demands strategic vetting to minimize erroneous inputs, it significantly amplifies spatial-temporal coverage (Themistocleous *et alii*, 2023). Through mobile applications, participants upload geotagged photographs or descriptions, which are then integrated into a central database for expert review and subsequent modeling. Crowdsourcing can also be utilized to collect information and embed it into the digital twin model by comparing the digital twin model with images that users send in real time (Themistocleous, 2024).

Public contributions, frequently facilitated by mobile applications or data provided by volunteer networks, provide geotagged imagery and qualitative observations at higher sampling intervals, particularly following extreme weather events. Automated validation systems and community training in basic diagnostic methods help maintain data quality. This public engagement fosters a shared sense of ownership and responsibility, often translating into broader support for cultural heritage preservation policies and funding initiatives.

Citizen engagement constitutes a fundamental component of the TRIQUETRA project, which employs a dynamic web and mobile platform to facilitate public participation in cultural heritage site monitoring. The crowdsourcing component of the TRIQUETRA project is designed to engage tourists, visitors and local communities in continuously monitoring and preserving cultural heritage sites. By leveraging a mobile and web-based application, the system enables users to contribute geotagged images, descriptive site condition reports, and environmental observations that supplement traditional monitoring methods. In this way, crowdsourced imagery is indispensable for detecting initial indicators of environmental changes that may jeopardize the integrity of heritage sites.

Through the TRIQUETRA application, site visitors capture and upload geotagged imagery, producing crucial datasets that supplement and refine existing 3D models. These datasets are processed through a backend 3D modeling pipeline, which enhances digital site representations and detects early indicators of site deterioration (Themistocleous, 2024), thereby improving monitoring and management efforts. A simple QR code scan at the site grants users full access to these functionalities.

Additionally, the TRIQUETRA Citizen Engagement Application delivers an immersive Augmented Reality (AR) experience, informing visitors about critical features at risk, such as areas impacted by climate change or structural vulnerabilities, fostering awareness and encouraging conservation. By integrating physical environments with digital overlays, visitors can explore historical reconstructions and uncover subtler aspects of site vulnerability. An interactive 3D model viewer enables in-depth examination of high-resolution reconstructions, including annotated artifacts or structural elements that feature textual or audiovisual commentary on historical contexts, building materials, or ancient engineering practices. This AR functionality is powered by AR.js and the A-Frame framework, allowing users to overlay digital information onto real-world settings. Through AR.js, visitors can engage with historical reconstructions, interactive site elements, and informative overlays that deepen their understanding of cultural heritage sites.

The application fosters awareness of ongoing risks and encourages preservation initiatives by overlaying additional information, such as details on areas affected by climate change or structural vulnerabilities. Through integrating advanced technologies and community-driven participation, TRIQUETRA adopts a holistic approach to safeguarding cultural heritage. The project's framework is designed to be replicated, improving risk assessment and promoting active preservation efforts on a global scale.

Multidisciplinary monitoring

An integrated monitoring approach using remote sensing data, including satellite images, UAV photogrammetry and in-situ data to create a digital twin model, combined with virtual reality and augmented reality, can create an effective tool to monitor at-risk cultural heritage sites. Time-series analysis can provide valuable information using change-detection techniques to compare changes over time.

Using various technologies, including UAV photogrammetry, conducted at different time intervals, can determine site conditions and seasonal changes, which can be enhanced with satellite Earth observation data. Remote sensing analysis using high-resolution imagery can identify risks from earthquakes, floods, landslides, erosion, ground movement, and structural displacement. The combination of remote sensing and onsite observations, including field survey and ground-based data collection and observations, can be one of the most effective ways of monitoring cultural heritage sites and monuments in Europe. The data collected and integrated into a digital twin environment permit scenario-based simulations of events such as extended heavy rainfall or mild seismic tremors. Citizen input can provide valuable information to the stakeholders by sharing real-time data using web-based applications. (Themistocleous *et alii*, 2023).

RESULTS AND DISCUSSION

By integrating remote sensing outputs, in situ geodetic observations, UAV photogrammetry, and crowdsourcing data, the study provided valuable information regarding Choirokoitia's vulnerabilities. The InSAR analysis revealed small yet consistent displacement rates of an average of 0.03 m/year in highly localized slope segments, which indicates slow-moving but progressive instability. The in-situ data and photogrammetric modeling corroborated these findings (Figure 2). The results also confirmed that sudden temperature and humidity swings, especially during extreme weather events such as extreme rainfall in the winter and high temperatures during the summer, undermined the integrity of stone structures. Onsite observations have verified the presence of rockfall (Figure 3), which may pose a potential danger to tourist safety at the site. The digital twin model was particularly valuable for monitoring the site by integrating in-situ and crowdsourcing data.

The methodology featured in Figure 4 shows the process of interchanging data from the physical model to the digital twin model by providing information to the TRIQUETRA toolbox for assessing and mitigating climate change risks and natural hazards threatening cultural heritage. Citizen participation notably enhanced the rapid detection of changes within the site as visitors' photographs showed different site conditions. Also, the application developed (Figure 5) provided users with an elevated experience while visiting the site through a state-of-the-art digital presentation through an Augmented Reality application.

The application and backend platform rely on a robust technological foundation, ensuring scalability, reliability, and user-friendliness. Its intuitive interface allows visitors to explore 3D

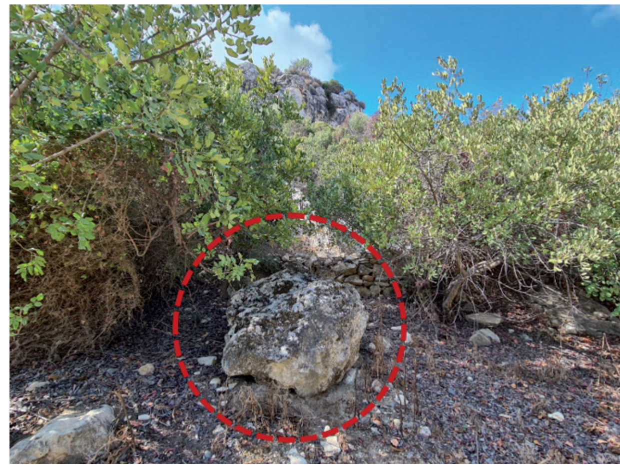

Fig. 3 - Evidence of rockfall in the Choirokoitia site is scattered in the Northwest area of the site

models, augmented reality features, and site information effortlessly. The application offers an informative and practical experience by providing insights into the site's history, climate change risks, and potential climate-related damages. A built-in questionnaire and feedback system enables visitors to contribute qualitative data about the site's condition, complementing the crowdsourced imagery.

Moreover, users can access the digital twin model for a virtual reality experience. Visitors may view this digital twin through VR goggles after leaving the physical site, allowing them to continue exploring in a virtual setting. Additionally, users can report potential climate-related damages by capturing and uploading photographs via their smartphones. These images are transmitted to the backend system, where they are made available to site authorities and integrated into the existing 3D model to detect any structural or environmental changes.

The Choirokoitia case study underscores the importance of a multifaceted monitoring framework, specifically illustrating

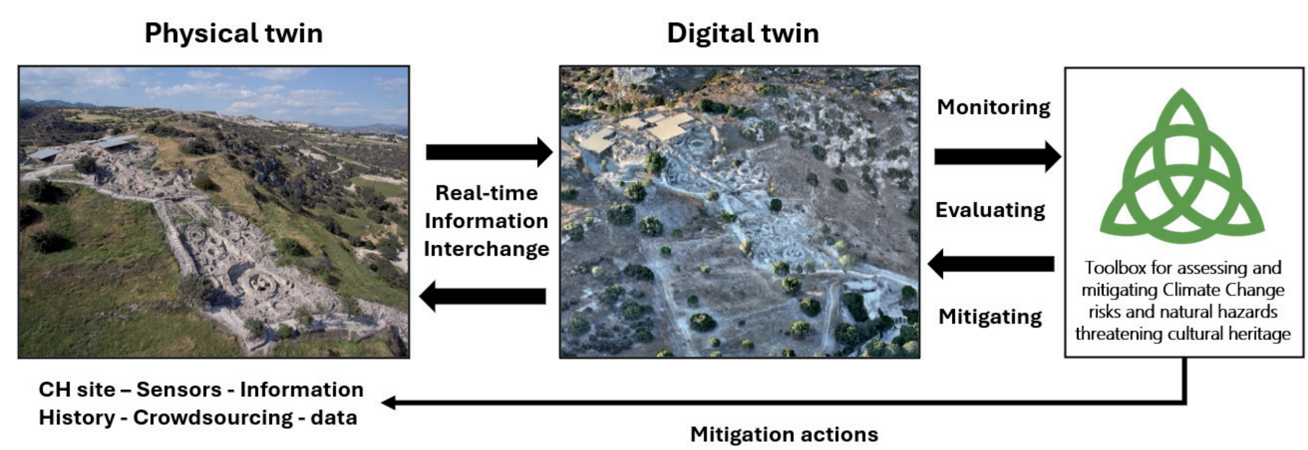

Fig. 4 - The methodology used to provide a real-time information interchange of the Choirokoitia UNESCO World Heritage Site is to monitor and evaluate the effects of climate change

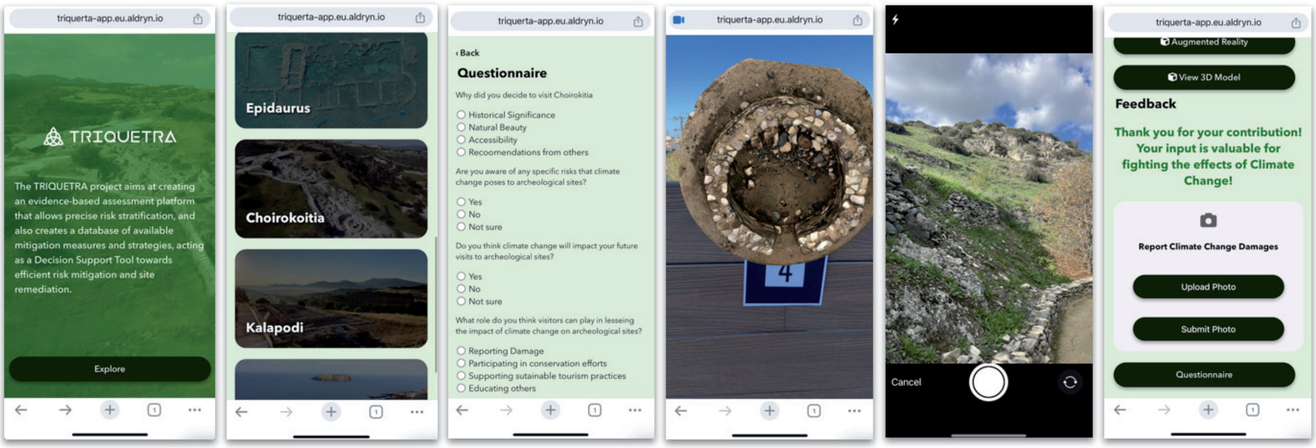

Fig. 5 - Overview of the application developed for the TRIQUETRA project to provide an elevated experience for the user while visiting the site by providing information, an interactive questionnaire and a state-of-the-art digital presentation through Augmented and Virtual Reality applications. The user can also upload images to report potential climate change damages. The photos are used to compute and update the existing site 3D model

how diverse methodological approaches converge to deliver both localized precision and broader contextual perspectives. Remote sensing methods, particularly InSAR, provide macro-level coverage that pinpoints deformation hotspots. In contrast, UAV-based imaging and geodetic stations contribute fine-grained measurements that are crucial for validating and interpreting the broad patterns noted by satellite data. The synergy of these tools exemplifies the comprehensive monitoring recommended by the TRIQUETRA project, showing that robust, evidence-based decisions emerge most effectively when multiple data streams reinforce each other (Themistocleous *et alii*, 2016; Themistocleous *et alii*, 2018; TRIQUETRA Consortium, 2022).

The added layer of crowdsourcing fulfills a critical role in bridging observational gaps, particularly for extreme events such as flash floods, hailstorms, or earthquakes. Citizen contributions enhance data frequency and build social capital around heritage preservation. Such contributions have broader implications for community-driven governance of cultural sites, wherein local stakeholders actively shape conservation priorities. Triangulation methods, leveraging AI-based image recognition and cross-checking with professional surveys mitigate data quality challenges (Themistocleous *et alii*, 2023).

Despite these successes, certain constraints remain. Implementing advanced methodologies, especially digital twins, can be resource-intensive regarding software, hardware, and technical know-how. Smaller heritage sites often lack consistent funding or trained personnel to sustain complex monitoring campaigns. Hence, knowledge transfer and capacity-building programs, possibly facilitated by EU-supported initiatives like PROTHEGO and TRIQUETRA, are essential to ensure the equitable distribution of technological benefits (Themistocleous *et alii*, 2016; TRIQUETRA Consortium, 2022).

Additionally, harmonizing data standards across different platforms and regions remains an ongoing challenge. Common data protocols, open-access repositories, and interoperability between remote sensing and cultural heritage databases would streamline international collaboration. Enhancing partnerships among universities, government agencies, and private technology firms could foster the development of cost-effective solutions and open-source software, democratizing advanced monitoring tools.

Policy Implications and Future Directions

The methodology implemented at Choirokoitia highlights a pressing need for targeted policy interventions that provide consistent funding, standardized guidelines, and capacity-building initiatives. International heritage bodies (*e.g.*, UNESCO, ICOMOS, and ICCROM) can play a pivotal role in championing best practices for remote sensing, digital twin simulations, and crowdsource monitoring. By embedding these approaches into broader cultural heritage management frameworks, governments can adopt evidence-based models that prolong the life cycle of significant sites while optimizing resources.

EU-supported initiatives such as the Green Cluster on Cultural Heritage with EU projects, including TRIQUETRA, THETIDA, RescueME, and STECCI, highlight how coordinated research and development efforts can bridge gaps between cutting-edge technology applications and traditional cultural heritage management. Funding mechanisms should prioritize fostering transnational partnerships to ensure that specialized equipment, technical assistance, and training modules reach culturally important yet under-resourced regions. This cross-pollination of ideas and expertise builds momentum for advanced heritage preservation.

Automated machine learning pipelines and Artificial Intelligence could refine anomaly detection by analyzing big data and large volumes of imagery collected by professional teams and citizens, revealing structural changes in near real-time. Innovative sensor technology may reduce costs and improve accessibility, allowing more sites to implement digital twins for monitoring cultural heritage sites and archaeolandscapes. Integrating climate modeling data into digital twins offers a means of anticipating how progressive climate shifts might exacerbate existing vulnerabilities in heritage settings. Finally, scaling up community engagement remains critical to establishing a robust culture of stewardship and inclusive governance models encourage local communities to invest actively in preserving their cultural narratives.

CONCLUSIONS

This paper has demonstrated the need for and the effectiveness of employing advanced remote sensing, geodetic technologies, UAV photogrammetry, digital twin modeling, and community-driven data collection to safeguard cultural heritage sites threatened by climate change, natural hazards, and geohazards. Drawing from research spearheaded by the TRIQUETRA EU project, the case study of Choirokoitia in Cyprus evidences how interdisciplinary and multiscale monitoring efforts can transition heritage management from a reactive to a proactive paradigm. Remote sensing offers a range of applications to monitor cultural heritage sites, with InSAR analyses pinpointing subtle ground deformations and UAV imagery capturing micro-level erosion. These data streams converge in a digital twin ecosystem, augmented by crowdsourced inputs, enabling real-time assessment and identification of changes.

Moreover, this integrative approach highlights the importance of both technological innovation and social engagement. While remote sensing, digital twins, and in situ instruments offer unprecedented precision in monitoring cultural heritage, community participation fills critical gaps in data acquisition, especially following extreme weather events (Figure 6). By linking the public more directly to heritage preservation, the TRIQUETRA model fosters broader societal support and enhances the capacity for long-term site stewardship.

Despite the complexity of implementing such comprehensive methodologies, the benefits of early warning capabilities, optimized resource allocation, and stronger community engagement justify sustained investment and policy support. Collaborative efforts among government bodies, academic institutions, cultural organizations, and local communities can magnify these successes. By committing to standardized protocols, open data systems, and shared infrastructures, the global cultural heritage sector can bolster resilience against intensifying climate hazards.

Future work should focus on scaling these approaches to a broader array of cultural heritage sites with diverse geographic and environmental profiles. Initiatives could leverage open-source software platforms and low-cost sensor technologies to ensure that even smaller, under-resourced sites benefit from modern monitoring methodologies. As climate change evolves, these strategies will remain indispensable for preserving the cultural and historical narratives that define our global heritage. Ultimately, preserving our cultural heritage sites transcends mere structural integrity; it safeguards the invaluable narratives and identities woven into humanity's collective past. The proven strategies discussed herein are a roadmap for future initiatives that aspire to protect and celebrate cultural heritage in a rapidly changing world.

Fig. 6 - Evidence of unstable stones at the highest point of the Choirokoitia site, which can contribute to rockfall that occurs as a result of extreme weather events

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