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Climate Change Monitoring of Heritage Sites Using Digital Tools

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Abstract:
Cultural heritage sites around the world, including archaeological landscapes, historic urban centres, coastal monuments, and living traditions, are facing increasing threats from the effects of climate change. Changes in temperature, precipitation patterns, weather extremes, sea level rise, freeze/thaw cycles, and biological factors are contributing to the deterioration of cultural heritage sites. The inability of traditional monitoring practices, which rely on periodic inspections, to effectively detect the dynamic changes to cultural heritage sites has resulted in the increased use of digital technologies.

This paper identifies the major digital technologies deployed for the purpose of climate-responsive heritage site monitoring. The technologies include Internet of Things (IoT) sensor networks, satellite-based remote sensing and Interferometric Synthetic Aperture Radar (InSAR), Unmanned Aerial Vehicle (UAV), ground penetrating radar, hyperspectral imaging, machine learning-based risk modeling, and digital twins. The capabilities of the technologies are evaluated individually and collectively for the purposes of heritage site monitoring. Case studies from various environments, including coastal sites, Arctic environments, desert environments, and urban environments, are presented for the application of the technologies for the purposes of addressing specific heritage site risks.

The need for governance, investment, and engagement is also underscored in this study, emphasizing the significance of these aspects for ensuring that the benefits of new technologies are harnessed for meaningful conservation outcomes. The ethical aspects, data standardization, and capacity building, especially in resource-constrained areas, are also underscored as areas of priority. The concluding sections of the paper outline a framework for resilience, wherein digital monitoring can play a foundational role for adaptive management and the preservation of cultural heritage in the face of environmental change.

Keywords: Climate Change, Heritage Sites, Digital Monitoring, Remote Sensing, IoT Sensors, InSAR, Risk Assessment, UNESCO World Heritage.

Introduction

The interrelationship between climate and the material substance of cultural heritage is as old as civilization itself. Every stone, timber, ceramic, paint layer, and earth deposit that makes up the archaeological and architectural record of human achievement is subject to the physical and chemical processes that are driven by the atmosphere, which in turn is influenced by temperature, moisture, solar radiation, wind, and the living organisms that these factors support. What has changed fundamentally in the twenty-first century is not the interrelationship between heritage and climate, but the rate, scope, and direction of this interrelationship. Human-induced climate change has accelerated environmental processes that operated over centuries or millennia into a trajectory that is being experienced over decades or years, which is far beyond the rate that heritage sites and monuments can adapt to.

The figures are alarming. United Nations Educational, Scientific and Cultural Organization’s (UNESCO) 2021 report on climate change and World Heritage revealed that more than half of all World Heritage sites are exposed to considerable climate-related risks; coastal and polar sites are particularly vulnerable to sea-level rise and thawing permafrost, respectively (UNESCO, 2021). The Intergovernmental Panel on

Climate Change (IPCC) Special Report on Global Warming of 1.5°C published in 2018 revealed that even if global warming is kept to a limit of 1.5°C above pre-industrial levels, hundreds of millions of people and thousands of important cultural sites will still be at increased risk of flooding, drought, and extreme heat than before the industrial era (IPCC, 2018). In a groundbreaking study published in 2014, it was revealed that up to 136 UNESCO World Heritage sites may be affected by sea level rise and flooding by the end of the century under moderate emissions scenarios; many may even be partially or totally inundated by mid-century (Marzeion & Levermann, 2014).

In this context, digital monitoring tools have come to be recognized as a set of essential tools in the practice of risk monitoring, early warning, and management in the context of heritage assets. The confluence of advances in the miniaturization of sensors, satellite imagery, drones, wireless communication, cloud computing, and machine learning represents an unprecedented set of monitoring tools, which can be used for monitoring changes in the environment, for the detection of physical deterioration, for modeling future risk trends, and for communication with stakeholders in real-time or near-real-time. These tools are not merely additive in the sense of offering new tools for monitoring; they offer a qualitatively different form of understanding, which is continuous in time, comprehensive in space, detailed in spectra, and robust in statistical evidence, which was not possible for previous generations of heritage managers or conservators. In this paper, there is a systematic examination of these digital tools and the monitoring systems in which they are situated, with particular attention to the challenges that climate change-related threats present. It is argued that digital monitoring is not simply about the excellence of the technology, but also about the quality of data governance, institutional capacity, ethical responsibility, and community partnership. It is also argued that technology, no matter how excellent, will not save that which institutional failure, political apathy, and social inequality place at risk; but without the situational awareness that digital monitoring offers, even the most well-intentioned and well-funded heritage management efforts will be undertaken with a dangerous ignorance of the escalating threats to the heritage record.

The Climate Threat to Cultural Heritage

Temperature and Thermal Stress

One of the most pervasive and insidious impacts on the material fabric of heritage sites is the increase in mean temperature, which stimulates a series of thermal expansion and contraction cycles, operating day and night, season after season, over the entire range of building materials, and thereby inducing a progressive mechanical fatigue in stone, masonry, concrete, timber, and ceramic fabric. As mean temperature increases, the difference between maximum and minimum temperature in a given day also increases, reflecting a trend in continental and arid environments. This stimulates a greater amplitude of thermal expansion and contraction, thereby accelerating the rate of fatigue-induced micro-fracturing. For calcareous stone buildings, which are a dominant building material in the heritage zones of the Mediterranean, Middle East, and parts of South Asia, the combination of increased temperature and moisture cycling stimulates a series of salt crystallization processes within the pore structures of the stone, thereby inducing expansive pressures that stimulate progressive spalling and loss of surface fabric (Grossi et al., 2011).

The problem of degradation due to temperature is particularly critical for painted and decorated surfaces. The fresco paintings, polychrome woodcarvings, metal alloy artifacts, and organic textile collections are particularly vulnerable to temperature fluctuations within ranges predicted for the twenty-first century. The storage areas within museums or the uncontrolled interiors of monuments can experience temperature maxima much higher than the external environment during a heatwave episode, which can lead to chemical or physical transformations in a matter of hours. Besides, it has been anticipated that the effects of climate change would impact the indoor temperature of historic buildings, which would impact artwork preservation and thermal comfort through an increase in the demand for cooling by 15% for artwork preservation as a result of increased humidity levels by 2050 (Muñoz González et al., 2020).

Moisture, Flooding, and Coastal Inundation

Variations in precipitation patterns and hydrological processes are considered the most geographically expansive and operationally complex type of climate change threat to heritage resources. The increased intensity of precipitation patterns overwhelms drainage systems designed to handle historical precipitation maxima, resulting in flooding of underground archaeological deposits, basement-level historic fabric, and lower-lying heritage sites in the landscape. Hydroground processes that alternate between long-term droughts that dry and shrink waterlogged organic material and intense precipitation events that cause sudden saturation and waterlogging create a risk for previously stable wet-preserved organic materials that are subject to rapid oxidative deterioration (Fukao et al., 2019).

It is the heritage site type that is most at existential risk, being simultaneously subject to the impacts of gradual sea level rise, increasing storm surge events of greater intensity, and accelerated erosion as a result of heightened wave energy and changed erosion dynamics. The intertidal zone, where already the effects of wave action, salt spray, and periodic wetting and drying are extremely degradation-prone, is expanding both vertically and horizontally as sea levels rise and storm return periods shorten (Castagno et al., 2018). Among the most significant archaeological landscapes at existential risk are the Bronze Age coastal landscapes of the United Kingdom and Scandinavia, the pre-Columbian coastal middens of the Americas, and the early Holocene landscapes of the world’s continental shelves that were subject to inundation during the early Holocene period (Harff et al., 2016; López-Romero et al., 2014).

Cryospheric Change and Permafrost Thaw

In polar and high-altitude regions, the cryosphere of glaciers, ice sheets, sea ice, and snowpack, and permafrost, has been a repository of organic archaeological materials for millennia. Organic materials decompose quickly under warm conditions. Thawing permafrost, with its accelerating rate of thawing across the Arctic and consistently higher than modeled rates of thawing, is unearthing archaeological deposits with unprecedented quantities of organic materials for microbial decomposition and erosion (Hollesen et al., 2015). Once exposed to air and water, these materials deteriorate within years or months. This presents a brief and rapidly closing window of opportunity.

Indigenous cultural landscapes in the Arctic and sub-Arctic regions are currently experiencing some of the most dramatic, climate-change-driven transformations of any type of heritage environment on Earth (Solovyeva, 2024). Changes in sea ice are significantly impacting the spatial relationships between communities, subsistence resources, and ancestral places, which have significant implications for the transmission of intangible cultural heritage. Coastal bluff erosion, which has increased at a rate that in some Alaskan communities exceeds ten meters annually, is a dramatic result of the loss of sea ice and increased wave fetch (Barnhart et al., 2014). Digital monitoring tools that can track these rapid changes, and direct limited intervention resources toward the most at-risk sites, are not merely desirable; they are ethical imperatives.

Biological and Chemical Deterioration

Climate change also affects the distribution, diversity, and metabolic activity of the biological communities that live on heritage surfaces, with these changes often being directly linked to increased deterioration of the materials themselves (Mosoh et al., 2024). The colonization of heritage stone surfaces by cyanobacteria, algae, lichens, mosses, and vascular vegetation is known to have a positive correlation with temperature and moisture availability; with the extension of the growing season and increased precipitation in previously dry heritage environments due to global warming, previously pristine stone surfaces are being rapidly colonized at unprecedented rates (Gaylarde, 2020). Biofilm development, the most ubiquitous form of biological deterioration, enhances chemical dissolution of the stone substrates through the release of organic acids and chelating agents, as well as physical disruption of surface microstructure through the pressure of hyphae and root growth (Cattò et al., 2023; Gaylarde, 2020).

The atmospheric chemical changes brought about by climate change also influence the deterioration rate of materials. Although it is acknowledged that the gradual reduction of sulphur dioxide emissions in Europe and North America since the 1980s has minimized the effects of acid rain on heritage materials, it is also recognized that increased levels of carbon dioxide and urban ozone levels continue to influence carbonation and oxidation reactions in heritage materials (Gimeno et al., 2001; Mylona, 1996). The increase in temperature levels also enhances the rate of all chemical reactions, including those causing deterioration, making it difficult to model and manage the complex interplay of deterioration factors.

Digital Monitoring Technologies: An Overview

The digital monitoring of heritage sites under climate stress involves a wide variety of digital technologies with different spatial scales of operation, frequencies of operation, and physical sensing modalities (Table 1). At the finest scale of operation, in situ sensor networks placed on or integrated into heritage fabric measure local microenvironmental conditions of temperature, relative humidity, surface moisture, salt ion concentration, structural vibration, and displacement. At intermediate scales of operation, close-range remote sensing systems based on ground platforms and UAVs monitor changes in surface conditions, cracks, and biological infill on individual heritage monuments and monument complexes with centimetre-to-millimetre spatial resolution (Piroddi et al., 2025). At landscape and regional scales of operation, satellite-based remote sensing platforms offer temporally continuous monitoring of entire heritage regions, monitoring sea level changes, coastal erosion, land subsidence, fire impacts, and vegetation changes over regions extending from single heritage sites to entire heritage corridors of thousands of kilometers in extent (Fu et al., 2024).

The integration of the information obtained from these multi-scale monitoring streams within a unified platform of analytics, increasingly referred to as a digital twin of the heritage site or landscape, enables a comprehensive situational awareness necessary to detect emerging threats, assess deteriorations, model future risk scenarios, and plan management responses (Mazzetto, 2024). Machine learning algorithms, fed by monitoring information combined with historical documentation and scientific studies of deterioration, enable automated anomaly detection, classification, and forecasting, which enhance the interpretive power of heritage managers and assessment specialists (Samudra et al., 2023). Collectively, these technological tools represent a qualitatively new paradigm of monitoring, and their implementation requires a corresponding investment in data, analytics, professional training, and governance.

Table 1. Summary of Digital Monitoring Technologies for Heritage Sites

Technology	Scale of Operation	Key Parameters Monitored	Main Applications	Advantages	Limitations
Internet of Things (IoT) Sensor Networks	Local (site-specific)	Temperature, humidity, vibration, moisture	Microclimate monitoring, structural health	High temporal resolution, real-time data	Maintenance, data overload
Satellite Remote Sensing	Regional to global	Vegetation, land cover, sea level, deformation	Landscape monitoring, climate trends	Large spatial coverage, long-term datasets	Moderate resolution
Interferometric Synthetic Aperture Radar (InSAR)	Regional	Surface deformation, subsidence	Structural stability, ground movement	Millimeter precision	Complex processing

Unmanned Aerial Vehicle (Drones)	Site to local	Surface cracks, erosion, biological growth	Condition assessment, damage mapping	High spatial resolution	Weather dependency, limited flight time
Ground Penetrating Radar	Subsurface	Soil structure, buried features	Archaeological and geotechnical analysis	Non-invasive	Interpretation complexity
Hyperspectral Imaging	Local to site	Material composition, biological growth	Early deterioration detection	High diagnostic capability	Expensive, complex
Machine Learning Models	Cross-scale	Pattern recognition, anomaly detection	Risk prediction, automation	Efficient large dataset processing	Requires training data
Digital Twins	Integrated multi-scale	Combined datasets	Simulation, decision-making	Holistic analysis	High cost, technical expertise

Internet of Things (IoT) Sensor Networks and In-Situ Monitoring

Microenvironmental Monitoring

IoT sensor networks, consisting of spatially distributed networks of sensing nodes wirelessly connected and continuously sensing and reporting environmental information, are at the base of in-situ heritage monitoring. Current IoT sensor nodes are capable of detecting temperature, relative humidity, carbon dioxide concentration, light intensity, surface wetness, structural tilt, vibration frequency, and electrical resistance, all of which are collectively indicative of the micro-environmental conditions causing degradation, in battery-powered nodes of dimensions comparable to or smaller than a matchbox (Hernandez & Cañas, 2024). The wireless communication capabilities of Bluetooth Low Energy, Long Range Wide Area Network, Zigbee, and 4G/5G cellular networks enable data transmission from remote areas, and nodes with solar-powered operation and energy harvesting capabilities can operate indefinitely without battery replacement in sunny outdoor environments (Georgakakis et al., 2011).

Significantly, the temporal resolution of IoT monitoring, which can capture parameter states at a scale of seconds or minutes over monitoring periods of months or years, represents a significant improvement over the information provided by periodic manual inspections, which are conducted at a much lower resolution. Critical deterioration processes, for example, salt crystallization, condensation, temperature shock, and freeze-thaw cycles, are generally on a timescale of hours, and long-term trends in these processes are accumulated as repetitions of individual events that might not be captured within a weekly or monthly monitoring period. IoT monitoring can provide long-term trends in the conditions within the microenvironment, which are used as the basis for attributing observed changes in these conditions due to climate change (Hernandez & Cañas, 2024).

Structural Health Monitoring

Structural health monitoring (SHM), on the other hand, is an extension of in-situ sensing from the environment to the direct measurement of the response of structures to loading: deformation, cracking, vibration, settlement, and tilt (Liew et al., 2025). Crack displacement meters (tell-tales and vibrating wires), tilt meters, fiber optic sensing cables, and distributed acoustic sensing are examples of technologies being used for heritage structures under the umbrella of SHM (Fischer et al., 2019; Zhu et al., 2022). They offer continuous records of the response of structures to loading and can detect the onset of instability before it is visible to the naked eye.

Fibre optic sensing systems, where strain and temperature changes are sensed by their effect on the optical properties of a continuous fibre optic sensing cable, are particularly well suited for use in heritage SHM applications owing to the fact that the sensors can be easily deployed by gluing them to the structure or embedding them in the mortar between the bricks, and can provide spatially distributed strain and temperature change information over the entire fibre length rather than point information at specific locations. The Brillouin optical time-domain reflectometry (BOTDR) method can be used for fibre cables of up to several tens of a kilometre in length, making it particularly well suited for the SHM of large and spatially complex heritage structures such as bridges, aqueducts, city walls, and cathedral vaults (Lv et al., 2025). Long-term SHM datasets can be cross-referenced against environmental datasets to calibrate empirical deterioration models that relate specific climate factors to structural response factors, providing the necessary mechanistic information for reliable predictive risk modeling.

Geotechnical and Groundwater Monitoring

Where the stability of heritage sites is influenced by subsurface geotechnical and hydrological conditions, in situ monitoring will need to extend below ground level in order to measure soil moisture, groundwater level, pore water pressure, and soil deformation that affect slope stability, foundations, and buried deposit preservation (Pirone et al., 2015). Piezometers, inclinometers, extensometers, settlement instruments, and time domain reflectometry (TDR) soil moisture measurement devices, among others, provide the necessary subsurface monitoring data that will help detect geotechnical warning signs of ground movement and instability before they develop as structural distress on the ground surface.

The integration of geotechnical monitoring with both atmospheric and structural monitoring is considered vital for heritage sites in areas where active slope instability is a problem, with thousands of such sites around the world, many with important archaeological landscapes or historic hilltop settlements, because the relationship between rainfall events and slope movement is nonlinear with thresholds, requiring the monitoring of both the driving force (rainfall intensity/duration) and the geotechnical response (antecedent moisture content/geotechnical strength) to provide reliable early warning (Themistocleous et al., 2018). Climate change is altering both components of this equation in many environments, with increased intensity in rainfall and changes in the patterns of antecedent wetting/drying that affect the thresholds for rainfall-induced slope failures.

Satellite Remote Sensing and Interferometric Synthetic Aperture Radar (InSAR)

Multispectral and Hyperspectral Monitoring from Orbit

Satellite-based optical remote sensing enables temporally repeated and spatially consistent coverage of heritage sites and their environments that range from individual buildings to entire cultural landscapes, allowing for the detection and tracking of change processes over months to decades. The archives of the Landsat program, with data going back to 1972, and the Copernicus Sentinel-2 mission, with global coverage at ten-meter resolution and a five-day revisit time since 2015, represent the most temporally consistent record of land surface changes anywhere in the world, making it invaluable for the assessment of the impacts of climate change on heritage sites and their environments (Tapete & Cigna, 2018).

Satellite imagery at multiple spectral bands can be utilized to carry out the spectral characterization of vegetation cover, soil moisture, water bodies, and surface mineralogy within heritage landscapes, which can further be used to detect drought stress within heritage-related vegetation, map flood extent and duration during extreme events, track coastal erosion and changes along shorelines, and monitor the impact of wildfires within heritage landscapes. The near-infrared and red band ratios of satellite imagery, particularly the Normalized Difference Vegetation Index (NDVI), can be used as a sensitive indicator of changes in vegetation health, which can detect changes in the early stages of drought stress weeks before visual signs of stress become apparent.

Interferometric Synthetic Aperture Radar

InSAR, which uses the phase of radar signals acquired at different times by orbiting SAR systems to detect millimetre-scale surface deformation, is arguably one of the most potent digital tools that can be employed to address the problem of slow-onset climate-related heritage threats. Ground subsidence resulting from groundwater abstraction, sediment compaction, and permafrost degradation; slope movements and creep in heritage landscapes subject to soil moisture changes; and land level changes resulting from glacial isostatic adjustment and sediment loading in the coastal zone are detectable at the scale of hundreds of square kilometres with precisions of millimetres per year using the InSAR technique.

The European Space Agency's (ESA) Sentinel-1 mission, which offers free global access to SAR data, has greatly democratized access to InSAR monitoring data, which has enabled systematic deformation monitoring of heritage sites and urban historic centers that would have necessitated costly commercial satellite data acquisitions (Tzouvaras et al., 2019). Multi-temporal InSAR (MT-InSAR) techniques, including Permanent Scatterer (PS-InSAR) and Small Baseline Subset (SBAS), have successfully extracted deformation time series from archives of dozens to hundreds of satellite data acquisitions, separating deformation from atmospheric noise and providing highly precise velocity and deformation histories for individual measurement points corresponding to persistent radar scatterers on heritage structures and archaeological earthworks. The techniques have successfully addressed a range of applications, including subsidence monitoring of the historic centers of Rome, Venice, and Bologna, as well as permafrost thaw-induced ground deformation monitoring in Arctic region archaeological sites (Tang et al., 2016).

Satellite-Derived Sea Level and Coastal Change Monitoring

Altimetric satellites, including the TOPEX/Poseidon, Jason, and Sentinel-6 missions, offer accurate information on sea surface height and its temporal change, respectively, across the world ocean, representing the primary observational dataset of sea level rise at the global and regional scale. Together with tide gauge data and GPS-derived information on vertical movement of the land, relative sea level rise projections can be generated, which take into account the difference between sea level rise and land level change, the quantity of interest for operational heritage site management. The spatial heterogeneity of sea level rise at the regional scale, due to ocean dynamics, effects of ice mass loss, and site-specific geology, means that the value at individual heritage sites can vary significantly from the global mean, requiring site-specific analysis based on the best possible dataset combining altimetric, tide gauge, and vertical land movement information.

Satellite-based change detection techniques enable the systematic monitoring of morphological changes in the coastal environment of heritage sites, which include changes in shoreline retreat, beach volume changes, dune erosion, and changes in the intertidal environment, using multi-temporal satellite imagery from optical and SAR sensors. The ESA Climate Change Initiative Coastal Hazards product and the United States Geological Survey (USGS) Coastal Change Hazards Portal offer processed data on coastal changes, which are computed from global satellite image archives, offering heritage site managers pre-computed rates of change and uncertainty for a range of global coastal environments. Combining these with DEMs and SfM-based topographic surveys enables inundation modeling for different levels of sea level rise and storm surge, which are used for risk modeling in adaptation planning.

Unmanned Aerial Vehicle (UAV) Surveys and Close-Range Remote Sensing

Systematic Condition Assessment by Drone

The use of UAV surveys is now at the heart of systematic condition surveying for heritage sites subject to climate change degradation, and this temporal surveying capability—i.e., surveying at set time intervals and comparing results to measure change—enables drones to be used for more than just surveying, but also for monitoring. The use of repeated photogrammetric surveying of heritage buildings, rock art sites on cliff faces, earthworks along coastlines, and other features at set time intervals of months or years can produce three-dimensional models and high-resolution orthomosaics of surveyed areas, which can be compared using change detection algorithms to measure loss, crack formation, biological growth, water staining, and structural change at sub-centimeter resolutions (Park et al., 2025).

The flexibility of UAVs as operational platforms is seen as particularly important for post-event assessment of heritage damage caused by extreme climate events such as storms, floods, wildfires, and landslides. The ability to quickly deploy and assess damage extent before any recovery work begins is critical for insurance purposes and scientific documentation of the impact of climate events. The use of thermal infrared cameras carried by UAVs can detect moisture intrusion, cracks, and drainage issues through the thermal signature of differential evaporation and heat capacity. These cannot be seen by optical sensors.

Multispectral UAV Monitoring

Multispectral sensors integrated on UAV platforms provide an extension of heritage condition monitoring beyond the visible range, where the biochemical and structural properties of deteriorated materials and biological colonizers are detectable. Near infrared reflectance is highly sensitive to the presence of biological growth, such as algae, cyanobacteria, lichens, mosses, on stone surfaces, which enables the characterization of the extent and density of biological colonization over monument surfaces at spatial resolutions that detect early stages of colonization prior to visual detection. Time series multispectral monitoring datasets enable the measurement of the rate of expansion of biological colonization and relate this rate to environmental climate factors, providing empirical data for the assessment of the climate sensitivity of biological deterioration mechanisms.

The technique of ultraviolet-induced fluorescence imaging, with suitable drone camera systems adapted for operation in the ultraviolet part of the spectrum under suitable low-ambient-light conditions, offers the potential for monitoring the effectiveness of various types of organic consolidants and surface coatings and weathering products on heritage surfaces. Light Detection and Ranging (LiDAR) scanners mounted on drones offer an extension of the potential for monitoring surface changes over three-dimensional heritage objects and locations where surface changes due to weathering and structural damage occur, such as densely vegetated locations and structurally complex ruined buildings, where surface obscuration by vegetation and structure would interfere with photogrammetric monitoring (Xing et al., 2025).

Hyperspectral and Thermal Imaging

Hyperspectral Analysis of Material Condition

Hyperspectral systems, which measure surface reflectance in hundreds of contiguous, very narrow bands of the electromagnetic spectrum within the visible, near-infrared, and shortwave infrared regions, offer much greater diagnostic potential for characterizing material condition and deterioration processes than multispectral systems. The distinctive spectral characteristics of stone mineralogy, weathering, salts, biological crusts, consolidants, and atmospheric soiling allow for the identification of many different kinds of deterioration processes at once, giving a complete picture of monument deterioration, rather than snapshots of single processes at a time.

Ground-based and close-range hyperspectral imaging systems, mounted on a tripod or scaffold structure, can achieve spatial resolutions of millimeters to centimeters, which are relevant to deterioration processes at the block or mortar joint level (Kurz & Buckley, 2016). Time-series hyperspectral imaging, where a series of campaigns are compared using spectral change detection techniques, can detect the onset of salt efflorescence, discoloration, and weathering crust formation before any notable loss of material occurs, thus providing the necessary warning time required by preventive conservation. The spectral characterization of biological colonization, through the identification of characteristic absorption features of certain pigments within the near-infrared range, enables the differentiation of colonizer species and the assessment of colonization health and activity, which is vital for biocide treatment strategies (Kiefer et al., 2010).

Thermal Infrared Monitoring

Thermal infrared images measure the heat radiation emitted from surfaces, which can be used to measure surface temperature and identify patterns of differential absorption, retention, and loss of heat based on properties of materials, configuration, moisture content, and subsurface features. In heritage buildings, thermal images are primarily employed for detecting moisture content within buildings, i.e., damp areas resulting from leaks in roofs, groundwater, or condensation, which can be easily detected as areas of unusually cool surface temperature due to evaporative cooling, and for detecting subsurface features such as voids, delamination, and other structural discontinuities based on thermal characteristics during cycles of heating and cooling.

Applications related to the monitoring of climate change effects via thermal imaging technologies are specifically focused on the documentation of extremes and the geographical spread of temperature extremes on the heritage surfaces during the occurrence of heatwaves. This approach can provide the necessary empirical evidence for the assessment of the thermal loads experienced by specific types of heritage surfaces under extreme weather conditions. Long-term thermal monitoring via fixed camera installations or the use of drones equipped with thermal imaging cameras and scheduled survey patterns can provide the necessary datasets for the assessment of trends related to the maximum surface temperatures and the occurrence frequencies/intensities of thermally stressful conditions, which can be used to provide the necessary evidence for the assessment of the effects of climate change on the deterioration of heritage surfaces.

Digital Twins and Integrated Monitoring Platforms

The Digital Twin Concept in Heritage Management

The digital twin, defined by a digital model of an asset that is constantly updated and reflects real-world conditions based on sensor data feeds, represents the most comprehensive and integrated use of digital monitoring technology for heritage management (Colace et al., 2026). A digital twin of a heritage site or monument would combine real-time sensor feeds with a three-dimensional geometric model of the site created by laser scanning or photogrammetry, periodic survey results from drone and satellite monitoring, historical documentation records, material property databases, and climate model projections to represent a digital model of the current state and future evolution of the site with unprecedented comprehensiveness. The strength of the digital twin approach is that it provides a framework for the integration of data with a high degree of variability in spatial and temporal resolution within a physically consistent three-dimensional space. Data recording hourly changes in temperature using IoT sensors at particular points on a stone facade may be placed in the context of the overall climate trends being recorded using satellite remote sensing; drone surveys recording changes in surface recession over months may be referenced to the high-resolution baseline geometry recorded using laser scanning; InSAR data recording changes over years may be referenced to data recorded using SHM systems recording changes in particular elements of the structure. Such data fusion allows deterioration processes to be understood over a range from the molecular to the landscape scale within a consistent framework, and deterioration projections to be made with a degree of specificity that was previously impossible.

Platforms and Implementation

Various platform architectures have been developed to accommodate the implementation of digital twins for heritage, and these platforms vary in their capabilities for geometric accuracy, sensor integration potential, analytical capabilities, and accessibility. Building Information Modelling (BIM) platforms, with modifications from their original use in construction via the Historic Building Information Modelling (HBIM) methodology, offer a rich and detailed three-dimensional modelling platform for representing the material composition and construction history of complex heritage structures (Murphy et al., 2017). HBIM models with sensor data linkages, condition survey records, and material property databases offer practical management tools for heritage management organizations in Ireland, Italy, Spain, and the United Kingdom.

Game engine platforms, such as Epic Games' Unreal Engine and Unity Technologies' Unity, have emerged as significant platforms for the development of heritage digital twins with physically based rendering, real-time lighting simulations, and support for virtual and augmented reality-based interfaces for navigating complex three-dimensional environments. Geographic information system (GIS) platforms, such as Environmental Systems Research Institute's (ESRI) ArcGIS Pro and Urban Digital Twin, provide the geospatially referenced environment for the development of landscape-scale monitoring-based heritage digital twins with satellite remote sensing, sensor feeds, climatic modeling, and risk analysis results within a spatially consistent framework (Ene et al., 2026).

Machine Learning and Predictive Risk Modelling

Automated Detection and Classification of Deterioration

Machine learning techniques for heritage monitoring data analysis have significantly changed the feasibility and efficiency of systematic condition assessment of heritage sites. Specifically, convolutional neural networks (CNNs) have shown high accuracy in detecting and classifying various types of deterioration phenomena in photogrammetric images, close-range photographs, and drone images (Shi et al., 2025). These techniques have shown great potential for the rapid processing of image sets too large for human experts to examine comprehensively. Object detection techniques, such as YOLO (You Only Look Once) and Faster R-CNN, for heritage surface images have shown great potential for detecting various types of deterioration phenomena with processing speeds several orders of magnitude faster than human experts (Gao et al., 2025). This makes systematic monitoring surveys of large monument inventories feasible for the first time.

Anomaly detection algorithms, when applied to IoT sensor data, facilitate the automated detection of unusual patterns in the microenvironmental or structural monitoring data that may signal incipient deterioration events or instability conditions. This type of unsupervised machine learning has also been successfully applied in environmental monitoring scenarios, where anomaly detection was used for the detection of unusual patterns in complex multivariate data sets for air quality monitoring (Owhe & Durodola, 2025). Long Short-Term Memory (LSTM) neural networks, which are particularly suited for sequential data analysis, have also been used for the prediction of future sensor readings based on recorded history, thereby facilitating the detection of unusual patterns that signal potential issues.

Climate Risk Modelling and Scenario Analysis

With the integration of projections from climate models with deterioration models for heritage, a quantitative assessment of future climate risk for a given heritage site can be made, thereby providing the evidence base for adaptation planning and prioritization of investments. Regional projections from CMIP6 (Coupled Model Intercomparison Project Phase 6) models, which are downscaled for scenario-dependent temperature, precipitation, and frequency of extreme weather events, are being used in the context of physically based deterioration models for projecting future deterioration rates for different materials for given emissions scenarios (Li et al., 2021).

The Monte Carlo simulation approaches, which use uncertainty propagation through deterioration models based on probability distributions of climate and material parameter inputs, offer probabilistic risk projections, which are more representative of a range of possible future outcomes rather than specific trajectories. The probabilistic nature of risk projections is critical for risk communication and adaptation decision-making for heritage sites, as it allows managers to express their confidence levels and scenario dependencies of risk projections, rather than expressing them as certainties based on single-value projections. Furthermore, the Bayesian network models, which define the probabilistic relationship between climate, deterioration, and heritage outcome metrics, offer flexible probabilistic models for quantifying uncertainty, which can accommodate different types of evidence, including monitoring, expert judgment, and historical, within a single uncertainty quantification framework.

Case Studies

Venice and the Historic Adriatic Lagoon

Venice and its lagoon are arguably one of the most intensively monitored heritage sites that are dealing with multiple facets of a complex global climate change issue: sea level rise, storm surge flooding (acqua alta), subsidence, saltwater intrusion into the building stock, and the growing frequency and intensity of extreme precipitation events. The Centro Previsioni e Segnalazioni Maree (CPSM) maintains a dense network of tidal monitoring stations throughout the lagoon that supply real-time tidal level data that is used to drive the acqua alta prediction system with a forecast horizon up to seventy-two hours in advance. The MOSE (Modulo Sperimentale Elettromeccanico) flood barrier system, consisting of 79 mobile flap gates that are raised to protect the lagoon from storm surges that exceed 110 cm above a reference datum, operates on the basis of forecasts that are driven by real-time data—direct integration with digital data and physical heritage protection infrastructure (Pirazzoli, 2002).

The European research infrastructure HERACLES (Heritage Resilience Against Climate Events on Site) has established comprehensive multi-sensor monitoring installations in selected buildings in Venice, utilizing IoT-based microenvironmental monitoring, SHM, and periodic drone-based photogrammetry surveys within a digital twin approach, in order to understand the impacts of the cycles of acqua alta on the deterioration of historic masonry and plaster materials (Bulatov et al., 2018). The long-term monitoring results from these installations have provided evidence on the salinization of the masonry on the ground floor, the acceleration of plaster detachment after flooding, and the moisture dynamics in historic sections of the buildings, which affect the rate and timing of salt crystallization damage. These results are currently used in combination with projected climate scenarios in order to model the future deterioration of the monitored buildings, considering different scenarios for sea level rise, in order to support the cost-benefit analysis of proposed adaptation solutions, which include improved drainage, targeted waterproofing, and even the potential relocation of the collections from the most vulnerable buildings.

Stonehenge and the Chalky Downland Landscape

The World Heritage Site designated in 1986, the "Stonehenge, Avebury, and Associated Sites World Heritage Property," is a Neolithic and Bronze Age ceremonial landscape. The chalk soil, which has successfully conserved the earthwork monuments, ditch fills, and buried deposits of this landscape for the past 5,000 years, is highly susceptible to climatic impacts, such as increased intensity of rainfall in winter, which saturates the top chalk layer, thereby enhancing erosion of the earthwork surfaces that are not protected; drought and heat stress, which kill the short turf that covers the flanks of the earthworks; and intense rainfall, which causes surface runoff and subsequent gully erosion in stable areas.

Historic England, the national heritage protection body for England, has designed a long-term monitoring programme for the Stonehenge landscape, which incorporates the use of satellite remote sensing, drone photogrammetry survey work, weather station information, and soil moisture measurement to monitor the condition of earthwork monuments and their response to changing climate conditions. NDVI-based time-series analyses of Copernicus Sentinel-2 satellite images have been undertaken to monitor the seasonal and inter-annual changes in the condition of turf cover over the landscape, identifying drought-affected areas where targeted watering and/or re-seeding is required (West et al., 2018). Comparative survey work from drone photogrammetry has been undertaken at two to three-year intervals since 2015 to quantify the recession rates of earthwork surfaces at individual monuments, providing information on differential response to climate conditions (Mencía et al., 2024). This information is being used to inform the design of erosion prediction models to forecast the future condition of earthwork monuments under future climate change scenarios.

Arctic Indigenous Heritage: The Case of Alaska

The indigenous villages along the coasts of western Alaska are considered some of the most endangered heritage environments on the face of the Earth, with a combination of permafrost thaw, sea ice loss, enhanced coastal erosion, increased storm surge penetration, and river flooding, in some locations consuming significant areas of these environments at a rate greater than ten meters annually. The Alaska

Native Villages Environmental Threat Assessment project, which brings together the United States Army Corps of Engineers, the Government Accountability Office, and Alaska Native Village organizations, has used UAV photogrammetry, multi-beam sonar, and GPS erosion markers in the measurement of the rate and extent of erosion in these endangered locations (Lim et al., 2023).

Community-based monitoring programs, whereby trained Alaska Native community members gather systematic data on environmental change using standardized digital recording technologies, such as geotagged photographs, GPS-based erosion measurements, and weather observations using satellite internet connectivity, have shown the effectiveness of using local ecological knowledge and scientific data in an integrated manner for a more comprehensive assessment of heritage under threat. Digital storytelling technologies, using a combination of geotagged oral history recordings, photographs, and contemporary drone-based images, are being developed in collaboration with Alaska Native communities for recording aspects of climate change-induced environmental change from a cultural perspective, thus creating digital heritage records of environments likely to change or disappear within a single human generation.

Institutional and Governance Dimensions

Policy Frameworks and International Initiatives

The overall governance structure for the monitoring of heritage sites for climate change ranges from the micro-level of individual heritage site management plans, through national strategic plans, to international conventions, and involves a complex of institutional actors, including UNESCO, International Council on Monuments and Sites (ICOMOS), national heritage offices, research universities, non-governmental organizations, and community organizations. The UNESCO Operational Guidelines for the Implementation of the World Heritage Convention, specifically to address the issue of climate change risks, include provisions that state that State Parties shall ensure that provisions for the assessment and monitoring of risks from climate change are included in the management plan for an inscribed heritage property, thus providing a baseline expectation for systematic climate monitoring as a condition of World Heritage stewardship (Lafrenz Samuels & Platts, 2022).

The Climate and Culture Alliance, created under the auspices of ICOMOS, is developing methodological standards for climate vulnerability assessment, monitoring protocol development, and data reporting that are meant to facilitate the practice and comparative analysis of climate change impacts on the world heritage sector as a whole. The research program of the European Union, Horizon Europe, has sponsored several consortia, including HERILAND, STRENCH, and HYPERION, that are developing digital tools for integrated heritage site monitoring and climate resilience that are currently being tested at various locations across the Mediterranean, northern Europe, and beyond, creating methodological case studies and open-source tools that are freely accessible to the world heritage sector as a whole.

Capacity Building and Equitable Access

One of the primary difficulties facing the global application of digital heritage monitoring technologies is the stark disparity between the technical capabilities and financial resources of heritage management agencies in high-income and lower-income countries. The most advanced digital heritage monitoring technologies, such as InSAR time series processing, hyperspectral sensor systems, digital twins, etc., are only currently available to a handful of heritage agencies in Europe, North America, and East Asia, while the world's most vulnerable and scientifically interesting heritage sites are found in Africa, South Asia, Latin America, and the Pacific, where heritage agencies possess severely limited budgets and technical capabilities.

This inequality is not simply an ethical imperative; it is also a scientific and practical imperative, given the monitoring gap that this inequality represents and the fact that climate change impacts on some of the most important heritage sites around the world are not well understood. Capacity-building initiatives around the world, such as the UNESCO-supported training programme of the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) and the British Council-supported Cultural Heritage for Inclusive Growth programme, are developing curricula and delivery mechanisms for training heritage professionals in under-resourced contexts to utilize digital monitoring tools in an effective and maximized fashion with tools such as open-source GIS software, smartphone-based photogrammetry software, and IoT hardware.

Challenges, Limitations, and Ethical Considerations

Data Management and Long-Term Preservation

The constant nature of the operation of multi-sensor digital monitoring systems results in large volumes of generated data, which represent significant management issues for heritage institutions with archival infrastructure originally designed for significantly smaller and less frequent volumes of data acquisition. An IoT-based network of fifty sensors monitoring ten parameters at a rate of once a minute can produce over twenty-six million records in a year; a drone-based photogrammetric survey of a historic building of medium complexity can produce tens of gigabytes of raw image data and several gigabytes of processed model data; a satellite-based InSAR monitoring system for a historic urban center can require the management and storage of hundreds of SAR scenes annually. The management, quality control, long-term preservation, and accessibility of these large volumes of generated data require significant investment in data management infrastructure, which is often not considered in the planning phase of monitoring programmes.

There is a persistent issue related to the interoperability of the information gathered through the system, as different monitoring programmes often use incompatible information formats, coordinate reference systems, metadata vocabularies, and quality documentation practices. A growing standardization infrastructure is the creation of specific data standards for the various domains; however, the use of this infrastructure within the wide range of the heritage monitoring practice is limited.

Ethical Dimensions of Digital Monitoring

The ethical issues posed by the use of digital monitoring technologies at heritage sites are issues that have not been fully addressed. In inhabited historic urban centres, spaces are shared among communities, who are not informed or have a say about the activities of the monitoring systems, including sensor networks and drone systems. The concept of informed consent, which is often required for research activities involving human subjects, is not always applied in digital monitoring systems at heritage sites, creating tensions between the scientific benefits of such systems and the rights of communities to self-determination in their shared spaces.

The use of machine learning algorithms for risk assessment also carries risks of perpetuating a lack of transparency and accountability of algorithms, as well as their inherent bias. The risk of algorithms trained on data from technologically sophisticated and well-resourced heritage sites being applied for risk assessment of sites in other, less well-resourced contexts is also significant, since they may systematically misclassify deterioration phenomena specific to different climatic and cultural contexts, and produce risk assessments that reflect the interests of technologically dominant institutions rather than those of the people whose heritage is being risk-assessed. Critical heritage studies scholars are increasingly arguing for the need for digital monitoring programs to be designed with specific attention to issues of whose heritage is being monitored, for whose benefit, and with what consequences.

Future Directions

Artificial Intelligence-Enhanced Early Warning Systems

The next generation of heritage climate monitoring systems may be marked by a much deeper integration of the application of artificial intelligence across the entire data pipeline from sensor data quality control and anomaly detection through deterioration mechanism classification and risk projection to adaptive management recommendation. Artificial intelligence rule generation frameworks, as seen in the application for network intrusion detection systems, point to the potential for automated pattern recognition and response mechanisms for heritage monitoring environments (Durodola, 2025). Federated learning-based approaches to the training of artificial intelligence models, where training is done collaboratively across distributed datasets without the need for the sharing of the datasets themselves between different institutions, point to the potential for the creation of powerful global monitoring intelligence while respecting the sovereignty concerns of the various institutions and communities.

Real-time artificial intelligence-based early warning systems, which combine information from continuous sensor inputs, weather forecasts, and predictions of deterioration models, could offer heritage managers alerts regarding deterioration risk events that are expected to exceed threshold conditions within a certain time window. The most important use of such systems lies in environments where events caused by climate factors occur rapidly and in unpredictable ways. These include coastal storm surges, flash floods, fire fronts, and extreme heatwaves, which demand immediate protective action. The combination of digital alerts and heritage first response procedures and emergency management protocols is a major challenge in the development of comprehensive climate resilience.

Community-Based Digital Monitoring Networks

Scaling digital heritage climate monitoring to the entire global heritage inventory, which contains not only hundreds of thousands of registered heritage locations within national heritage registers but also millions of non-registered heritage locations that are considered important by local communities, requires a monitoring strategy that goes beyond the capabilities of professional survey teams and incorporates the monitoring capabilities of local, engaged communities. Participatory monitoring schemes, whereby professionally trained members of local communities use standardized digital technologies to systematically collect and upload heritage condition data, have shown that scientifically valuable heritage monitoring data can be collected on a scale and spatial extent that is not possible through professional survey alone.

Mobile applications specifically developed for heritage condition monitoring, including guided observation protocols, standard terminology for the classification of deterioration, geotagging and timestamping, and the ability to upload data to central repositories, are being developed by heritage agencies and research centers around the world. The incorporation of citizen science monitoring information and professional sensor network and satellite remote sensing information within a unified platform requires a critical consideration of the issue of data quality assurance and the communication of differential measurement uncertainty. The proper design and support of citizen science monitoring networks hold a potentially profoundly scalable and empowering alternative to technologically intensive professional monitoring schemes, which alone cannot hope to achieve global coverage.

Climate-Adaptive Heritage Management Frameworks

The ultimate goal of digital climate monitoring is not data accumulation, but rather the facilitation of enhanced heritage management decisions, including decisions regarding the prioritization of conservation investments, the selection of appropriate conservation strategies, the timing of protective measures, and the planning of heritage site utilization and access in the context of shifting climatic conditions. However, the process of translating monitoring data into enhanced heritage management intelligence is not possible without institutional frameworks that address the substantial gap between monitoring data and heritage management decisions, which is arguably the most outstanding challenge in heritage climate adaptation.

Climate adaptive management frameworks, wherein the assessment of the present condition and future risk paths is embedded within a cyclical approach to management planning with specific provision for strategy revision as conditions change, represent the ideal outcome for digital monitoring programme development. In this approach to management, the information from the monitoring programme is not seen as a static end-product to be filed away in an archive, but rather as a dynamic input to an ever-evolving system of management intelligence whose analytical products are reviewed, communicated, and implemented through accountable governance practices. The creation of this ideal outcome for digital monitoring programme development requires investment not only in the technical infrastructure for the programme but also in the cultural and professional environments through which technical information can become the basis for effective and equitable heritage management.

Conclusion

The dominant issue for heritage management in the twenty-first century is climate change, for which monitoring systems have to be developed that are comparable in scope and depth to the issue being addressed. Digital technologies such as IoT sensors, satellite imagery, UAVs, hyperspectral imaging, digital twins, and machine learning have the unprecedented capability to detect and counter the emerging challenges posed by climate change. Case studies have been presented for a range of areas such as Venice, Alaska, and Stonehenge that show the diversity of the issue and the success of different digital monitoring strategies for different areas. The key to success in heritage management is institutional commitment, community engagement, and adaptive management; data alone is insufficient for success. The next steps in the development of heritage management must address new areas such as the development of new monitoring technologies, data standardization, capacity development in vulnerable areas, and ethics development. Climate change is a global issue that surpasses geographical boundaries; therefore, the strategies for its monitoring must also transcend geographical boundaries for the first time with the help of digital technologies that have the capability to address this issue at a suitable scale.

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