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Digital Heritage Preservation for Fragile and At-Risk Sites: Standards, Ethics, and Access

Kakembo Aisha Annet

Faculty of Education, Kampala International University, Uganda

ABSTRACT

Cultural heritage sites across the world are increasingly threatened by climate change, armed conflict, environmental degradation, and limited governance capacity, making their preservation an urgent global priority. This paper examines the role of digital heritage preservation as a strategic response to safeguarding fragile and at-risk sites. It explores key standards and frameworks, including metadata systems, provenance tracking, and interoperability models that support sustainable digital preservation practices. The study further analyzes methodological approaches such as three-dimensional (3D) documentation, geospatial technologies, multispectral imaging, and the development of digital twins for monitoring and conservation planning. Beyond technical considerations, the paper critically engages with ethical dimensions, including rights, consent, cultural sensitivity, and community participation, emphasizing the importance of inclusive and context-specific approaches. It also addresses challenges related to long-term accessibility, storage, digital obsolescence, and the digital divide, highlighting the need for equitable access models. Through an integrated analysis, the paper argues that effective digital preservation requires a balance between open access and protective restrictions, supported by strong governance, international collaboration, and sustainable funding mechanisms. Ultimately, digital heritage preservation is presented as a vital tool for maintaining cultural memory, enhancing global access, and ensuring the continuity of heritage for future generations.

Keywords: Digital Heritage Preservation, Fragile and At-Risk Sites, Metadata and Provenance, Cultural Heritage Ethics, Digital Access and Equity

INTRODUCTION

Much of the world's tangible and intangible cultural heritage is fragile and at risk due to physical degradation, climate change, political and economic upheaval, competing governance priorities and other threats [1]. Digital heritage preservation, especially using access-oriented and community-based approaches has emerged as a key prescription for safeguarding such heritage [2]. Widespread yet uneven attention to digital preservation has spurred the development and dissemination of various frameworks around the globe, with limited direct connection to the emerging international standard on digital preservation [3]. These challenges are compounded in fragile-and-at-risk contexts, where governance, equipment, and knowledge are often constrained. Digital approaches to heritage preservation promise the potential to deepen engagement, extend access, and reduce on-site interventions without compromising human oversight [4]. Fluctuating investment in digital initiatives; external or shared ownership of the original analogue; competing priorities for conservation and curatorial attention; and uncertainty around custodianship, rights, and ongoing financial support are important practical, technical, and socio-political factors that can limit the applicability of digital approaches for capturing, protecting, and enhancing information about tangible heritage[5].

The Challenge of Fragile and At-Risk Sites

The fragility and vulnerability of certain cultural heritage sites present an ever-greater challenge to the long-term preservation of collective memory [1]. The importance of heritage, especially for risk-prone societies, was underscored when, tragically, the world lost a UNESCO World Heritage Site: the Old City of Aleppo, Syria, an historically cosmopolitan center that dates back thousands of years, as a result of civil war. Through armed conflict, economic hardship, urban development, river management, and climate change, numerous coping strategies are available. Within this context, a vital response is digital preservation [2]. Memory institutions face ever-increasing wars, natural disasters, and urban development that threaten documentary and cultural heritage collections. According to UNESCO, "Convention Concerning the Protection of the World Cultural and Natural Heritage", cultural heritage especially refers to buildings, monuments, historical sites, and archaeological sites [3]. Documentary heritage refers to documents such as manuscripts, pamphlets, books, maps, and photographs. There is no one-size-fits-all approach to combatting conditions that threaten cultural heritage, yet several measures can guide digital preservation of fragile and at-risk heritage sites [4]. Extensive degradation, such as peeling paint from wall murals, decay of canvas from paintings in unmaintained public spaces, and dilapidation of pathways, advanced archival programmes and procedures, have led to difficult access and limited public enjoyment[5]. Fragile and at-risk heritage sites face increases in such deterioration and require high-priority digital documentation to capture the current state, provide detailed condition maps, enable timely intervention, and ensure continued revitalization [1]. Simultaneously, competing priorities for governance and funding often limit resources for the digital preservation of cultural and documentary heritage, a situation that has become particularly evident in the context of Open Data Plans being developed in many jurisdictions worldwide [2, 3].

Standards and Frameworks for Digital Preservation

Ensuring digital preservation requires standards and frameworks that facilitate not only the establishment of effective processes, but also the interoperability of solutions across disciplines and delivery platforms. While technical guidance can be derived from several relevant initiatives [4], the UNESCO Charter on the Preservation of the Digital Heritage emphasises alignment to established international principles, notably regarding the rights of the individual, the need for national co-ordination in the collection of materials, and the balance between enterprise and individual requirements [5]. Frameworks, standards, and guidelines developed to address specific digital archives and their materials, such as the Open Archival Information System (OAIS) Reference Model, Digital Material and Data, and the Data Protection Act find these requirements reflected in their principles [2]. The temporal dimension of fragile and at-risk digital heritage further suggests the need for defined provenance chains, to capture such actions affecting the authentic delivery and repeatability of material [4]. The provenance aspect similarly relates to the significance of open material and its obligations to allow community control over access and embodiment [4]. Fundamental metadata, therefore includes; the declared raw and processed materials, the defined aim of the first action undertaken, the identity of the authoring agent, the date on which the action occurred, the undertaken action itself and the declared intended future actions to be engaged further upon it[5]. In addition, for transparency the ability to describe which segments of data each action particularly affects and to initialize or continue an audit trail upon delivery of data into other domains of control[6].

Metadata and Provenance

Digital heritage preservation for fragile and at-risk sites: present evidence-based rationale; define scope, and state objectives [5]. Digital preservation involves the systematic management of digital materials over time to ensure ongoing access and enable future uses [6]. Materials subject to digital preservation activities include documents, photographs, maps, drawings, audiovisual materials, three-dimensional models, and scientific data, among many others. The preservation of digital records is considered especially challenging because digital materials rapidly degenerate without careful management and software-based systems generally dictate their daily use [2]. Digital materials may undergo damage simply as a result of their creation, with each successive access or modification further injuring them [7]. For fragility/at-risk sites, a sophisticated understanding of the formal characteristics of access is fundamental to preserving records in the most open form possible. Digital preservation also requires attention to propagation chains and multiple concurrent uses in a period of rapidly changing governance and policy while grappling with the need to monitor and document the digital preservation process itself [6].

Digital Formats and Long-Term Accessibility

To ensure long-term accessibility of records, preservation planning should incorporate a comprehensive consideration of technical sustainability, covering multiple aspects of digital formats and frameworks [16]. Digital material remains physically intangible, demanding specific algorithms, equipment, and infrastructure for effective ongoing usage [17]. Yet no formal guarantees exist regarding the future access to, or usability of, most recorded material. Common archival formats, computer operating systems, and audiovisual equipment become relatively obsolescent within one decade of their introduction, and the ongoing ability to maintain open or adequately-supported access to all recorded digital material over the long term remains deeply uncertain [18-20]. Even under the most robust long-term public engagements, active preservation requests remain vital for many peripheral

components of the global digital ecosystem [21-25]. Within numerous domains, the continued adequate coherent operation of larger models, simulations, or immersive visualizations may also require systematic supervision of the computer algorithm, software code, performance system, or device used for presentation [26-27]. The formal definition of digital sustainability should also explicitly address the distinctive conditions which frame preservation planning, outreach engagement, and remote accessibility for many highly fragile and endangered heritage records at the international scale [28-30]. Widespread public interest in fragile sites already exists. Such engagement commonly remains nevertheless inevitably limited by steep challenges of secure access and extensive site conservation carried on alongside any form of digital stewardship initiative [31-33]. Further, large international initiatives associated with crucial, pioneering public and scholarly engagement on such records now routinely describe and govern the situation as "modern multimedia" rather than "digital," and formal requirements for such terminological adjustments then systematically extend thereafter to encompass the additional constraints of format preservation alongside the preservation of content itself[11].

Storage, Storage Geographies, and Economic Considerations

Digital preservation, long a preoccupation of cultural institutions has gained renewed urgency as fragile and at-risk heritage sites come under intensified threat [3]. Numerous standards and framework documents define the principles, practices, and technologies of digital preservation [9]. Each identifies similar objectives, stressing principles such as interoperability, sustainability, and cost-effectiveness, yet only a few harmonize fully with widely adopted, international guidance [10]. Interoperability is increasingly critical in a world of multivocality where agreement on digital-preservation strategies is seldom universal and where the interplay of different, locally defined approaches to preservation cannot be neglected [11]. The difficulty is compounded when preservation is facilitated in numbers of locations under diverse institutional governance and commercial arrangements. In these circumstances, working with widely adopted standards promotes coherence and shields part of the digital heritage archiving strategy from undue local contingencies [12]. Furthermore, documents such as the Open Archival Information System (OAIS) provide rigorously developed conformance criteria, enabling the integration of preservation solutions into broader policies concerning information management, heritage stewardship, risk assessment, and disaster recovery [13]. Digital-preservation metadata centers on ensuring authenticity and reproducibility. Authenticity addresses the question, "Is this what it purports to be?" Reproducibility concerns the capability to produce, using the same methods and materials, a replica, reconstruction, or proxy variation of the original. Metadata addressing these matters forms the backbone of a provenance chain that defines the progression of actions taken on a digital object and the decisions made along the way [14]. Unique identifier schemes address not just the item itself but also each composite creation. Digital-preservation planning, accordingly, encompasses three vital components: proper identification of the asset, the formulation of a comprehensive record of the provenance chain, and the establishment of audit-trail protocols to document each action [15].

Documentation of Condition and Risk

Online or physical heritage is subject to change and degradation over time, thus the first task in planning relevant preservation actions is to assess their current state [16-18]. This assessment establishes a point of departure for subsequent observations and actions, allows the planning of future actions, and identifies the most pertinent at-risk elements affecting its degradation [19-23]. Preservation action is usually spurred by the manifestation of the first indicators of deterioration [3]. Deterioration may take place in a wide variety of ways, from debris accumulating in niches in the case of rock art to changes in the shape of 3D elements, cracking of masonry, or appearance of biological colonization 10. Regular monitoring of these indicators is necessary for promptly reacting to these situations. In line with the risk assessment procedures recommended by UNESCO in its World Heritage Risk Management Toolkit [4], recording of the specific impact of each indicator on the selected at-risk elements and on the global heritage is useful. The same toolkit outlines the importance of classifying hazards according to their nature, intensities, and probabilities of occurrence [5].

Ethical Considerations in Digital Heritage

Digital timeliness depends on accessibility, reliability, and safety of the data. The main pillars are user-centred policy design, balanced openness and protective restrictions, and reinforcement of the digital infrastructure and access equity [5]. The human factor also plays a crucial role in project management. Many of the approaches and deliberations regarding access to digital content apply to both digital objects that are directly related to the site and hyperlinked or otherwise available documentation, information, pointers, or other indirectly related documents [6]. Careful consideration of rights, permissions, and community involvement precedes any digital heritage preservation initiative [7]. What to preserve, how to preserve it, and what policies to put in place to engage with the public requires dialogue, engagement, and focus on the values held by the custodial community or institution. Definition of custodianship is also important, especially when dealing with community-based heritage. The principles of stewardship rather than ownership as conceptualised by many in the field of indigenous heritage apply well in such situations [8]. The possibility to generate digital content without consent or even a definition of custodianship still exists in many bleeding-edge projects and initiatives, where open access is bundled with

social accountability [9]. Methods of recording digital heritage that corroborate with such approaches are the most widely implemented methods in various fields, either technology- or domain-driven. Digital contents bound to a site or site-related digital documents must remain open and free of charge [10]. The circle of safeguarding values and rights does not close on obtaining free-and-open licenses. Issues of respectful portrayal further emerge, especially in the case of digital heritage associated with marginalised communities or world-views outside rather extensive documentation [1].

Rights, Consent, and Community Involvement

Digital technologies have the potential to record, analyse and share heritage data more rapidly, accurately, and affordably than previously [6]. Nevertheless, digital documentation also raises important ethical questions about rights, consent, and community involvement which need to be taken into account in parallel with the technical planning [7]. For example, Indigenous peoples have historically faced the expropriation of knowledge and intellectual property without credit. Recently, many have used the very same digital technologies to reclaim control over traditional knowledge [8]. The emergence of community digital archives has encouraged considerable reflection about the ethics of digitisation in heritage organizations [9]. New funding paradigms, along with the economy of sharing digital content across the internet, have introduced additional ethical dilemmas [10]. The rise of new media offers different models for the recording, processing, and communication of heritage materials, fuelling public debate about the responsibilities of practitioners and the degree to which sensitive information should be shared [11]. Codes of ethics produced by cultural heritage organisations are beginning to address these evolving challenges. Community participation is a particularly salient theme: aesthetics, documentation choices, and even the legitimacy of recording are shaped by local people, and preservation and access frameworks should be tailored to local needs [1, 12].

Cultural Sensitivity and Representational Fidelity

Efforts are needed to ensure that valuable cultural heritage remains preserved, even as the contemporary world subjects it to various forms of neglect and deterioration [10]. Traditional, non-digital means of safeguarding these materials do not always suffice [11]. That said, digitally preserving cultural heritage also comes with ethical challenges, and applying a level of sensitivity when performing a action such as digitization can foster respectful representation and context-appropriate dialogue [1]. A respectful portrayal, one that does not cause harm, is fully contextualized in a meaningful way, and faithfully represents specific aspects of material culture, is important. If these standards cannot be met, then it may be preferable to choose a different object to digitize, seek guidance from the community involved, or convene a workshop to discuss alternative options [12].

Privacy, Security, and Forensic Readiness

Digital collection and widespread dissemination must balance the goal of open access with respect for privacy constraints. Sensitive information of various kinds geospatial coordinates, ethnographic details, unpublished research, archival correspondence, and other potentially harmful material, may accompany the documentation of fragile and at-risk heritage sites [1]. The requirement to safeguard such information often extends to planning for cybersecurity and forensic readiness, ensuring that digital documentation remains protected against inappropriate access, alteration, and loss [2]. The principles of digital preservation for fragile and at-risk heritage sites remain applicable to sensitive information [3]. Metadata describing sensitive material, restrictions on access or use, and conditions for future deletion or modification can be recorded along with the documentation, along with provenance metadata and an audit trail detailing actions taken. Respect for communal rights, such as the need to control and select what is disseminated, may require the systematic communication of contextual information as an integral feature of preservation and access policies [4].Separately, forensic readiness relates to establishing and documenting procedures prior to a security incident, so that an effective and appropriate response can occur when an incident is detected or suspected [5]. Relevant contextual information concerning threats, vulnerabilities, and consequences can be recorded, as may details of preventative and detective controls, configured security parameters, audit trails, backup policies, incident events and preliminary analysis, and post-incident reviews [6].

Access and Equity in Digital Heritage

Preservation agencies aim to provide maximum possible access to information objects while maintaining the integrity of fragile and at-risk sites [5]. Televisual and network-based dissemination methods provide powerful means of browsing and studying distilled records, yet promote uncontrolled dissemination that might damage the sites themselves [6]. These opposing elements create powerful inequities in the preservation of cultural heritage. The issue of access who participates, how they engage, and which features they experience deserves focused elaboration [7]. A user-centred philosophy won increasing favour in the initial decades of multimedia digital-environment development. Innovative designs undertook adaptation to socio-cultural, physiological, and digital-infrastructure differences, enacting more secure contextual and technologically streamlined pathways to world-situated phenomena [8]. Human-centred interfaces centrally engaged and adapted to specific-terrain people, understanding and shaping major particulars such as modes, media, access, and empowerment [1]. Essential world-situated and virtual-terrestrial qualities broadened from here into expansive explorations combining

austere, rich, rare, thin, layered, macro, micro, temporal, and other formal aspects [8]. Pathways to extend recording and other procedures often construct "virtual sites" capable of experimentally coating numerous pertinent and controllable traits without further jeopardising physically attested, sometimes tacky objectives. The term "formation" describes a group of particular-important and clarified co-variant tangible, perceptual, social, spatial, compositional, and situational characteristics[7]. Categorial gaps persist widely among distinguished historic developments, which regularly configure attributes as palimpsests (historical overlaying mingling with virtual-socio-technical transformation), hypostase (object-thing association layered in the field of objects), and so on [6]. The traditional digital-access dichotomy of "open" versus "restricted" remains salient. Open-access controls typically relax all access fields, refer to public-domain or comparable statuses, and differentiate indirectly from permission management filling specific rules for assorted non-public, semi-public tiers, or similar grades [5]. Emerging forms nevertheless elaborate further distinctions between particular access fields, permissions, and requisite holdings, reflecting stipulations, options, and steps governed within both types and classes [8].The growing urgency of the so-called digital divide/black hole stresses the dearth of physical, digital, and hybrid-wideband infrastructure for data burden and receipt, further inhibiting information-sensitive exchanges, participative-but-scenic adequacy-upgrading operations, permanently-mainstream shape-outer extensions, economical-catalyst-boosting supplementations, and discourse-sustaining social-broadcasts and proceedings [9. 10].

User-Centered Access Models

Digital heritage presents unique challenges for equitable access among diverse potential users. Visitation numbers invariably decline following the initial establishment of a site, and public attention can easily shift to competing registrants [11]. Digital access also acquires different meanings across layers of documentation, temporal, infrastructural, and rights-related [12]. Users are diverse, and straightforward, intuitive interfaces cannot accommodate the interplay among stakeholder groups, access models, languages, cultural considerations, and different types of data underpinning digital preservation work. Nevertheless, the need for a "user-centered approach" to access remains [12]. At the- perhaps–most basic level, the heterogeneous range of expected users prescribes the need for tailored digital experiences. The World Wide Web can accommodate tremendous diversity in interface design, but broad questions concerning language of choice, the extent of accessibility features, or engagement of different senses remain without firm consensus [13]. In project-based digital preservation settings, however, such concerns often receive scant attention beyond the initial decision regarding choice of working language [14]. Multi-layered, adjustable user-centering permits the system to engage and adapt to varied user profiles across materials and site types. This applies both during the archival stage, accompanying decisions on how to present specific data and cover vital contextual questions, as well as during the act of viewing [15].

Open vs. Restricted Access and Licensing

Accessing and sharing information about fragile and at-risk cultural heritage sites raises intricate questions regarding both preservation and access [1]. Such sites are sometimes subject to a zealous desire for full and open access to all documentation, even endangered sites, as is the case with some open data or open archives initiatives. On the other hand, some preservation stakeholders, including those with experiences that suggest unjust exploitation of fragile sites, wish to see access withheld altogether from all but a narrow set of registered, certified, secure, trusted, or otherwise validated users [2]. Such desire is often motivated by understandable fears that knowledge about sensitive archaeological sites may trigger unanticipated tourism, vandalism, pilfering, yet further decay, cessation of grants or support, military or police attention, or even cult or religious reactions[3]. In the balance, understanding how to accommodate both preservation ambition and responsible access seems crucial [12]. Disentagling this intricate and intricate narrative can, at least, begin to clarify how to handle the complicated access question [3]. In order to balance both preservation and access, it can be practical to delineate a stepwise description of what technical, ethical, and permanent elements a candidate organization or individual intends to address in its documentation [4]. Preparatory tasks, such as defining which materials (e.g., images only, tracings, point-clouds, videos) are covered and how they are generated, can be distinguished from legitimate operational activities such as metadata provision and information notation, each of whose rights are noted and discussed [5]. Technical and final objectives, such as which items are to be processed further over time, and any development of subsequent processing that the preserve of a further organisation or audience is considered to need attention, can likewise be covered too[6]. Such layered pacing, in other words, realizes a potential gradual construction of complex public access coverage of intricate and sensitive documentation on fragile and a-risk sites, while respecting the condition that, for various deterrent or minor reasons, extensive highly-processed access documentation may either be entirely avoided or may well take months or even years to arrange equitably and solidly [7].

Digital Divide and Infrastructure

Access to digital heritage materials should be equitable, especially since the preservation targets frequently involve the world's poorest and most marginalised cultures [2]. The gap between those who possess electronic

resources - computers, digital networks sufficiently robust for content consumption, or sufficient comprehension of such technologies, and those who do not remains considerable [1]. The issues of electronic storage and the governance of access thus acquire prime significance. Considerations of governance and bandwidth are intimately interwoven into such spaces as the allocation of space on the cloud, local server versus intrusion on others' systems, and the degree to which content can be downloaded without interference by others.

Methodological Approaches to Digital Documentation

Preserving fragile and at-risk locations requires a careful, well-balanced approach to planning and decision-making. Many sites experience preferring access restrictions and use cataloging systems employing advanced digital techniques [4]. By drawing on a variety of established practices, techniques, and technologies, practitioners can preserve temporary phenomena. Fragile sites include relatively ephemeral, yet culturally significant traces from previous geological, climatic, and environmental conditions [5]. Digital documentation also enables building robust knowledge of every site's past integrity and degradation while inferring timelines and predictions [10]. Multiscale 3D reconstructions guarantee complete and lasting replicas compatible with analysis at varying scales [3]. Detailed terrestrial and aerial recording (e.g., UAVs) assists in drawing geospatial correlation among multiple spot records covering wider areas [2]. High-resolution images offer enabling further advanced examinations, permitting digital twins and simulations of fragile materials and artifacts to anticipate decay and longer strategic conservation plans. Integrating multispectral analysis improves interpretation of coloring, surface alterations, and imperfections during archaeological analysis. Physical samples serve an extraction of archaeological knowledge, while assuring digital coverage [1].

3D Recording and Geospatial Techniques

The digital preservation of cultural heritage sites and objects in their original condition is impossible. Instead, the documentation of fragile, at-risk heritage may include the digital capture of site or object deterioration and change over time [3]. Documentation creates a wealth of knowledge that can be made widely accessible in many formats. Techniques from disciplines such as remote sensing, engineering, archaeology, and computer vision offer a range of options for preparing three-dimensional (3D) digital captures of the environment. Geospatial data can be supplemented with geological and material analysis, multispectral imaging, colour studies, and information from historical photographs [4]. Full 3D records provide input for expanded scientific investigations. Environmentally controlled digital twins can be constructed that let users explore preservation alternatives while assessing the effects of various disturbances or projected impacts of climate change [5]. Individual sites can often be monitored through non-invasive sampling and digital documentation, especially with rapid geospatial and spectral capture techniques [6]. Geospatial data recorded from the surface through terrestrial and aerial captures enables quantitative spatial analysis of structures, materials, threats, and spatio-temporal behaviours, elements that can be visualized while creating new interpretations of the heritage [13, 10]. Specifics of regionally adopted methods and selected capture studies are given in case studies.

Imaging, Spectral Analysis, and Data Fusion

Digital-preservation initiatives frequently center on 3D data acquisition and analysis, whether aimed at determining degradation parameters, recording changes over time, or providing benchmarks for restoration [3]. These practices draw on existing photographic data (e.g., consistent views of sites at distinct periods) and involve terrestrial or aerial capture to facilitate vegetation analysis, numerical modeling, photorealistic visualization, or the creation of geographic information systems (GIS) databases [14]. Nevertheless, valuable data about materials, surfaces, colors, texture, and physical-chemical state often lie beyond 3D digital capture capabilities. For many fragile or at-risk sites, distinctive materials, including plaster, stones, mortar, organic pigments, or wall paintings represent primary documentary evidence of ongoing transformations [15]. In these contexts, 3D documentation complements high-resolution color or multispectral imaging, 2D analogues of the former, that capture wear and damage evolution and address recording challenges specific to flat or planar objects [16]. Colour or multispectral acquisition permits the analysis of preventive preservation conditions and relata directly to the underlying materials and pigment mixtures supporting narratives, colorimetric assessments, or evolutive processes. Multispectral data facilitates the identification of responses to early deterioration phases, the graphical representation of ongoing transformations including fading, cleaning, or repainting, and the mapping of sensitive areas needing more careful conservation treatment or protective interventions [17].

Digital Twins and Virtual Reconstruction

In the context of fragile cultural heritage, a thoughtful preservation strategy involves the preservation of both material remnants of an object, whether digitized the object itself, its texture, surface, or color, and of an object's context [7]. Preservation strategies frequently involve the development of a digital twin or virtual replica of a site. As new data about the site's condition and changes to the site accumulate, a digital model of the site that reflects an understanding of the initial configuration and degradation of the object can also be appended [8]. Such a strategy supports the creation and use of a surviving digital record of a heritage site, a record that incorporates data gathered from the original heritage site into an ongoing, necessarily interpretative, modeling effort [9].

Digital models often applied to fragile cultural heritage include 3D computer-aided design (CAD), three-dimensional models, and graphical modeling/animation packages [10]. Tools that provide attractive rendering, lighting, and animation effects can be particularly useful in communicating potential movements, transfer of elements, and for assessing the site's integrity and risk of loss[11]. High-resolution models that capture surface features and support measurement can document condition, but even abstract models containing a few key parameters, location-size of fracture or loss, can serve predictive and prescriptive roles. The model does not require contemporary detailed data as input [12]. Development of a digital twin typically begins with geometric building information modeling (BIM), which represents the site's solid geometry; young programs that model the solid geometry of all objects within the same space of a heritage site can support the simultaneous modeling of an entire site [13]. Exchanges of geometry and property from one system to another are possible, but to permit long-term accessibility and simple conversion, a versatile geographic information system (GIS) with community datasets can be a strategic initial choice. Making the digital twin data as open as possible, while still respecting communities and stakeholder concerns and consent, is often important [10]. Optional attributes, condition, birth-date, ownership, version-tag, or modification-history can assist in tracking and managing such concerns throughout the modeling process [14]. The alternate modeling approach focuses on the precise preservation of form and aesthetics, seeking to reproduce an object with maximum fidelity to the original form [2].

Case Studies: Practices from Fragile and At-Risk Sites

Art and cultural objects have the duality of being deteriorative and significant as a heritage resource within a community. Due to their fragility, gathering information about these resources is vital [7]. Threats like vandalism or extreme weather events continue to jeopardise already precarious locations [8]. Important cultural heritage concerns arise when documenting these assets. One case of valuable information on such sensitive situations illustrates these tactics within the archaeological community [9]. The Kandahar provincial cultural heritage in Afghanistan faces serious detrimental direct and indirect consequences. Policies by the Government of the Islamic Republic of Afghanistan (GIRoA) and the Taliban both severely hinder the preservation of tangible artifacts and the potential intellectual documentation of the situation worldwide [10]. Under both regimes, Afghan citizens live in a state of constant fear, posing a major barrier against such efforts. Advice and material from responsible institutions like UNESCO and ICCROM are difficult to obtain. The need for safe and secure digital preservation of culture within Kandahar's archaeological community has reached a critical juncture [1].

Rock Art and Caves

Digital heritage preservation for fragile and at-risk sites encompasses an increasingly diverse array of sites and site types [7]. Rock art sites, caves, archaeological wetlands, delicate terrains, and architectural fragments stonemasons in eroding environments merit specific mention due to their glaring need for preservation and their propensity to be overlooked [8]. Rock art resilience already exemplifies competing governance priorities on the pathway to digital preservation [10]. Each case exhibits its own preservation challenges, ethical sampling limitations, and constraints on integrity-ensuring access [17]. A diverse range of rock art and cave sites exist, but the key challenge remains deterioration due to damage inflicted by the environment, site visitors, or both. Digital documentation emerges as the only viable alternative once physical preservation becomes impossible. Each rock art site is unique, and their representations should reflect this uniqueness. At the same time, the accessibility challenge inherent in, for instance, caves results in the risk of limited data sharing and even public dissemination of existing data through private collections [11]. Archaeological wetlands and delicate terrains comprise another category of sites requiring careful digital-presentation consideration. Moisture-sensitive records in these environments, combined with other preservation-to-sustain-conflicting high-risk site designations, give rise to competing preservation priorities. Requests to access such records continue to arrive from monitoring, research, and renovation components. Where documentation to support such efforts can be undertaken, it is performed without these sites entering public awareness [12]. Fragile architectural fragments damaged by water currents are progressively lost in coastal surrounds and navigable river locations. Increasing frequency and intensity of rainfall damage these melt-water eroded remains. Projects in progress and earlier studies continue to monitor affected fragments [13]. Nevertheless, when erosion affects elements with social significance, such as inscriptions that provide cultural links, enhancement facilitation, or movement shaping, modern activities remain in place, necessitating a broader perspective that embraces ongoing document ability [14]. Fragment inclusions sometimes reveal watermarks that facilitate provenance elucidation during preservation reflection. Slight material changes attributable to later interventions may still be recorded without requesting permission. Moreover, simplicity when forming physical restorations can evade politically sensitive topics [15].

Archaeological Wetlands and Delicate Terrains

Preserving archaeological installations in underexplored wetlands and ephemeral open terrains poses multifaceted challenges [11]. Sites within the expansive Tenere Desert of Niger are eroded by high winds, while moisture-sensitive records embedded in permafrost maintain their integrity in the Arctic and Antarctic regions. General

guidelines facilitate the selection of preservation priorities, restoration standards, and environmental monitoring procedures for sites at risk [12]. The erosion of Venetian skyscrapers dating from the Gothic Revival to 2006 prompted the acquisition of digital documentation. Accessible versions remain restricted to public audiences lacking permission for broader use [3]. Prioritizing locations across fragile wetlands, archaeological epochs, temporal depth, and material constitution, the Dominique Perrault project has secured digital replicas for retention at risk of daily loss of history and knowledge. Moisture-sensitive preservation records embedded in open terrains or wetlands at risk of swamping and drying out would similarly benefit from prior documentation. Early indications show that large sand depositions promote conditions for prehistorical dying events, revealing traces of biogenic origins [11]. The fragile and extraordinary nature of trails accounts for further aerial stocking. Hence, delicate muddy terrains composed of terrestrial, fluvial, and marine strata subject to de/rehydrating cycles would merit the attention of documentation. Several sites catalogue microbiological biofilms, including cyanobacterium microbialites harbored within minerals and permafrost-embedded Ice Age faunal remains both under semi-arid and arid climates [12]. The enduring scientific value of such terrain remains closely linked to their original configuration, encouraging careful duplication of the focused configuration through the public domain [10].

Architectural Fragments in Eroding Environments

In ruins extensively damaged by erosion, including historical architecture, pillars, and decorative elements, nearby surviving fragments are often valuable for reconstructing the original structure [13]. Such fragments warrant careful capture and study, with a focus on site provenance, restoration implications, and reverse effects such as increasing awareness of the surface condition of at-risk structures [13]. Existing data capture may be subject to time and space limitations at fragile neo-Gothic façades and lattice work [2].

Governance, Policy, and Institutional Roles

Responsible governance and clearly defined institutional roles critically influence successful digital preservation for fragile and at-risk sites [14]. International coordination is essential to implement cross-border policies arising from treaties such as the World Heritage Convention and the 2003 Convention for the Safeguarding of the Intangible Cultural Heritage. Consultative documents establishing International Guidelines generally advise alignment with global standards, advocating for protection, preservation, and integrity [5]. Responsibilities relating to heritage documentation and preservation in both physical and digital formats have been articulated within the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the World Organisation for Animal Health (OIE) frameworks. Many institutions and governments develop preservation norms consonant with these overarching principles [14]. Precise designation of curatorial and research obligations informs decisions regarding the subsequent usage of documentation that addresses sensitive aspects, such as fragile physical structure, theft and illicit trafficking, or indigenous peoples' heritage, in accordance with international best practices [18]. In addition to international frameworks, funding agencies and governments demand clarity on the form and extent of prepared documentation so that they can establish sustainable support and ensure appropriate institutional recognition [14]. Describing and analyzing these economic models permits the identification of viable trajectories and optimal authorities for sustainable digital preservation, thus enhancing stewardship commitment [14].

International Collaboration and Standards Bodies

Digital preservation of fragile and at-risk sites is a global challenge involving various international accords that seek to regulate and standardize national and private initiatives [15]. Many of the corresponding legal frameworks, organizations, and coordinating bodies are coordinated through the UNESCO initiative on the Memory of the World Programme, the Intergovernmental Research Group for Information Preservation in Africa, Global Environmental Facility, the International Council for the Preservation of Archives (ICPA), European Union (EU) Copyright Directive, and a multitude of other resources offered by members of the National Digital Information Infrastructure and Preservation Program (NDIIPP)[15]. The concept of digital preservation is evolving to accommodate recent developments in computational capacities and technological applications [16]. As an example, national preservation strategies documented within the framework of the UNESCO General Conference Reflecting Only on Safeguarding Digital Heritage have gained much attention. Nevertheless, the challenge of balancing appealing and informative content and safeguarding remains widespread [16]. Prioritization of different types and locations of heritage is needed to coordinate preservation efforts and achieve a balance between emphasizing the appealing aspects of fragile sites whilst guiding the public back to preservation issues that motivated the not-for-profit networks [17]. Further investigation into communities' needs, drives for website migration, support for a balance between accessibility and protection for digital objects connected with fragile sites, and an exploration of non-digital yet related subjects remains pertinent [17].

Curatorial and Research Responsibilities

Digital preservation entails the responsibilities of careful selection, supervision or support for preservation efforts, and establishment of the conditions for continued preservation or use [18]. These curatorial and research duties can be collective, systemic, and institutional, or they may belong to individuals or small groups [18]. In disciplines

where written documentation is less central, such as the visual arts, architecture, music, and dance, the nature of curation and research is especially susceptible to influence from institutional frameworks and architectural distributions [19]. Digital preservation is inherently a collective, community-based undertaking, but the involvement of global social networks and the overspill of public action on the scale determined by advances in mass communication technology have massively extended the geography of personal agency and practice [19]. In practice, curation and research are often intimately intertwined through preparation and proposal generation, and they remain inseparable in many challenging or underrepresented domains [19].

Funding, Sustainability, and Stewardship

The financial model and organizational structure required for continued digital preservation of fragile and at-risk heritage resources remains context-specific, and multiple options exist [20]. The anticipated lifecycle of digital objects, the community of benefit and anticipated forms of use dictate the most appropriate and viable preservation and access arrangements [20]. Models range from highly centralized, government-funded arrangements to institution-driven models, to models dependent on electronic publications funding supported by the user community. Commercial, for-profit archives also offer preservation services [21]. Cost-sharing arrangements realized by regional or subject-based initiatives are other possibilities. Stewards of digital resources should consider preservation measures from the beginning of digitization to ensure long-term sustainability. Creating culturally appropriate histories of the sites and communities involved can also foster future support [21].

Risk Management and Disaster Preparedness in Digital Contexts

Preserving digital content from fragile and at-risk sites requires coordination of preservation planning, intervention activities, and condition documentation. Digital rebroadcasting offers significantly expanded access to social media platforms; however, there are related risks of loss and unrestricted dissemination of sensitive content [22]. The impact of site loss may justify informal sharing if widely acceptable, but digital heritage preservation of continuums for fragile and at-risk sites action demands greater consideration [22]. Either fragment may unaccountably enter unpermitted states leading to further modification, undisclosed reconstruction, or expenditures on dismantling; this drives interest in site sharing and the extent to address shifted planning requirements reversing access, the construction can obscure the original condition; thus, said plans generally include preparation of digital heritage fragments, and even institutional definition of the related policies [23]. Redundancy of copies, consideration of scenario-based migration attention, and evaluation of emulation pathways further contain options for directing effort from sites towards digital Considered incident response includes recording tasks assigned per role, communication channels, and phased illustrated restoration capability[23].

Redundancy, Migration Planning, and Emulation

Institutional and personal collections alike are at risk of becoming inaccessible due to the obsolescence of digital media [23]. Fragile media, rapid acquisition and reorganization, size, uncertainty about artwork but incorrect labelling, and multiple custodians further complicate preservation [24]. As compulsory measures, creation of multiple copies, preemptive planning for digital media migration and consideration of possible emulation are needed for the long-term retention of collection materials [24].

Ethical Deaccessioning and Data Minimization

Digital heritage preservation operates under the dual imperatives of protecting fragile and at-risk heritage and encouraging wider and more equitable access [23]. All forms of accessibility, including digital preservation, entail risk of exposure or removal of other data from circulation. Accordingly, digital deaccessioning and restrictions on data dissemination present critical issues requiring careful consideration [24]. A systematic decision-making framework for determining which data may properly be deaccessioned, restricted, or left available must be devised based on an evolving understanding of the values involved in data transparency and the circumspection occasioned by such uncertainties [24]. Rigid adherence to particular protocols is unlikely to prove useful for sites in flux with emergent or deteriorating restrictions on data accessibility or display. The ethical questions hinge on the nature of the data in relation to various stakeholder rights, control, visibility, and risk of harm. Data-minimization and deaccessioning directly involve retention and restriction of-location, user, and usage data, as well as other information stemming from a site [25].

Incident Response and Recovery Protocols

A disaster is usually defined as a serious disruption of the functioning of a community or a society involving widespread human, material, economic, or environmental losses which exceeds the ability of the affected community or society to cope using its own resources [25]. The type of disaster can range from natural (e.g., earthquake, floods, and storms) to man-made (e.g., fire, vandalism, and civil disturbance)[26]. Therefore, digital preservation of digitally archived assets is at risk from the moment they are stored in a digital archive. Similar types of incidents and disasters that caused damages have occurred in the past where the cultural service sector was impacted [26]. Examples of disaster scenarios that a digital project may experience are draught, flood, physical damages, and unauthorized access. In countries where arid climate is experienced, humidity can cause

multiple damages to human and cultural, artifacts, items and creation were lost. The African dry stone construction structures are examples of how dry climate can influence the construction [26].

CONCLUSION

Digital heritage preservation has emerged as an indispensable response to the growing threats facing fragile and at-risk cultural sites worldwide. This paper has demonstrated that while digital technologies provide powerful tools for documentation, analysis, and dissemination, their effectiveness relies on the integration of robust standards, sustainable frameworks, and interdisciplinary methodologies. Approaches such as 3D recording, geospatial analysis, and digital twin modeling not only enhance preservation efforts but also enable broader engagement with cultural heritage beyond physical limitations. At the same time, the study underscores that digital preservation is not solely a technical exercise but one deeply embedded in ethical, social, and cultural contexts. Issues of rights, consent, cultural sensitivity, and community ownership must remain central to any preservation initiative. The tension between open access and the need to protect sensitive information further highlights the importance of carefully designed access and licensing systems. Moreover, challenges such as digital obsolescence, infrastructural limitations, and the global digital divide continue to shape the accessibility and sustainability of digital heritage initiatives. Addressing these challenges requires coordinated international efforts, inclusive governance structures, and long-term investment in digital infrastructure and capacity-building. In conclusion, the preservation of cultural heritage in digital form is both a necessity and a responsibility. By aligning technological innovation with ethical principles and community engagement, stakeholders can ensure that fragile and at-risk heritage is not only safeguarded but also made meaningfully accessible for present and future generations.

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