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Article

Integrated Digital Environments for the Knowledge and Management of Low-Accessible Cultural Heritage: A Multiscale Web-Based Framework

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Abstract

Low-accessible Cultural Heritage, including hypogeal sites, rupestrian architectures, and fragile structures, represents a major challenge for conservation, documentation, and continuous monitoring. These limitations stem from multiple inaccessibility factors, classified as physical (morphological complexity), asset risk (microclimatic instability), health and safety (structural vulnerability), managerial (lack of public access), and cognitive (lack of documentation). This research aims to transform digital models from mere representational tools into integrated cognitive and operational systems supporting decision-making and preventive conservation. The proposed methodological workflow is structured into five main phases: Preliminary Knowledge and Multidisciplinary Data Structuring (Ph1. PK–MDS), Comprehensive Digital Survey (Ph2. CDS), Development of Integrated Digital Models (Ph3. IDMs), Advanced Diagnosis and Monitoring (Ph4. ADM) and the implementation of an Integrated Digital Environment for Hypogeal Heritage Management (Ph5. IDE). Ph4 operates on two complementary scales: at the site scale, range-based point clouds enable the semi-automatic identification of extensive decay patterns, such as biological colonization. At the detail scale, the Random Forest algorithm enables the segmentation and quantification of material loss on frescoed surfaces through a diachronic comparison of historical and current data. Validated on the San Pellegrino complex in Matera, selected as a paradigmatic case study of low-accessibility hypogeal sites, representative of a broader system comprising approximately 150 rupestrian cult architectures, the methodology demonstrates how immersive digital environments function as shared knowledge spaces, supporting more informed, inclusive, and resilient heritage conservative management.

Keywords: hypogeal heritage; semantic data integration; detection decay; conservation strategies; Virtual Reality; integrated digital models; digital proximity



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1. Introduction

The conservation and enhancement of low-accessibility architectural heritage currently represent one of the most complex and relevant challenges in the field of cultural heritage research. Hypogeal Cultural Heritage consists of an extremely heterogeneous set of underground structures and complexes which, although frequently analyzed as punctual, fragmented, and low accessible sites, can be more appropriately interpreted as a systemic network of hypogeal complexes. These assets are configured as spaces excavated

or constructed underground, distributed across the territory and characterized by marked morphological, typological, and site-related diversity, closely correlated with geological and geotechnical conditions, excavation and construction techniques, as well as the functions historically performed. Functionally, these spaces include residential and rupestrian hypogea, productive and artisanal environments, subterranean hydraulic infrastructures (such as cisterns, aqueducts, and drainage systems), places of worship and burial, defensive or refuge spaces, as well as hypogeal systems closely connected to stratified rural or urban settlements. This functional diversity corresponds to a wide range of typological configurations, from simple and isolated chambers to complex, interconnected systems, often developed on multiple levels and in direct relation with the overlying built structures [1]. From the perspective of construction techniques, hypogeal sites can be classified into two primary macro-categories, in which the function of the spaces is directly influenced by the mode of construction:

- (i) Rupestrian structures, characterized by shallow excavations into exposed rock outcrops. The direct shaping of the rock and the relative simplicity of excavation techniques allow the creation of limited-scale spaces, suitable for residential, cultic, funerary, or small-scale productive functions. The orientation, dimensions, and depth of these spaces are strongly conditioned by the natural morphology of the rock and the local geomorphological context.
- (ii) Underground structures, excavated deeply below ground level, where the technical complexity of excavation enables the development of more articulated and functionally diverse spaces. These include cisterns, galleries, hypogeal warehouses, refuges, and complex hydraulic systems, often arranged on multiple interconnected levels [2].

Functional diversity and construction techniques are expressed in significant morpho-typological variability, manifested in highly differentiated spatial configurations: ranging from simple, isolated environments to complex and interconnected systems, often developed on multiple levels and in direct relation to the overlying structures. Hypogeal heritage is therefore distinguished not only by the complexity of its spatial morpho-typological and constructional and decorative features, but also by the plurality of relationships established with the overlying settlement system and the natural landscape, assuming different roles within historic urban aggregates, rural contexts, or extended territorial frameworks. This classification reflects the multiplicity of historical uses and the social and landscape contexts in which these spaces were conceived and utilized, and aligns with contemporary research approaches that advocate for a comprehensive understanding of subterranean heritage as an integral component of the built heritage and the broader “Underground Built Heritage” [3]. Consequently, the technical knowledge and management process of such organisms requires a multiscale approach, capable of integrating detail-scale analyses, aimed at the documentation of individual hypogeal spaces or structures, and site-scale analyses, focused on understanding the spatial, functional, and historical relationships among the different units and their urban or territorial context, assigning specific levels of investigation to each scale.

In particular, hypogeal sites, rupestrian settlements, underground architectures, and, more generally, contexts characterized by structural fragility, microclimatic instability, and safety constraints constitute extremely vulnerable systems, in which natural and anthropogenic degradation processes intertwine in a critical manner [4].

In such contexts, the condition of “low accessibility” cannot be attributed to a single factor but rather takes the form of an articulated set of limitations operating at multiple levels. These include forms of low physical accessibility related to spatial configuration, the presence of obstacles, and the morphological complexity of environments; conditions of low accessibility associated with risks to people and to the asset itself, which make direct access

problematic or unsustainable; management-related limitations deriving from regulatory, organizational, or logistical constraints; and, finally, forms of low cognitive accessibility, attributable to the fragmentation of information, difficulties in data interpretation, and the lack of integrated tools for a systemic understanding of the site [5].

In this sense, low accessibility does not represent exclusively a physical condition but directly affects the possibility of constructing coherent, updatable, and transferable knowledge frameworks, influencing the entire process of analysis, interpretation, and heritage conservation and management.

Low accessibility, determined by morphological, structural, environmental, regulatory, or managerial factors, significantly compromises documentation, monitoring, and knowledge transmission activities [6]. In many cases, the impossibility of carrying out direct and continuous inspections renders these sites effectively invisible, characterized by discontinuous and fragmented documentation and difficult to integrate into ordinary conservation planning processes. Consequently, a substantial portion of architectural heritage, despite its high historical and cultural value, remains excluded both from fruition circuits and from effective risk management and prevention strategies.

Within this scenario, the digital transition applied to cultural heritage has opened new methodological perspectives for addressing the issue of physical inaccessibility [7–9]. The integration of advanced surveying techniques, diagnostic analysis tools, and immersive digital environments has enabled a rethinking of the processes of knowledge acquisition, interpretation, and communication related to fragile historic built heritage. Digital models, increasingly accurate in geometric, material, and chromatic terms, are no longer configured exclusively as representational tools but as genuine informational ecosystems capable of integrating heterogeneous data and supporting complex cognitive processes, in support of preventive conservation, long-term monitoring, and knowledge sharing among different stakeholders [10,11].

These digital ecosystems represent a transformative approach to heritage management, particularly in contexts characterized by limited accessibility. By integrating high-resolution geometric and colorimetric models, spherical imagery, textual documentation, and semantic annotations within a coherent digital framework, these ecosystems effectively overcome the informational discontinuity typical of low-accessible sites. This enables the introduction of what can be defined as a form of “Digital Proximity”: a scenario in which stakeholders (researchers, conservators, and sector professionals) can engage with the cultural asset virtually, exploring its spatial, material, and structural characteristics in a meaningful and measurable manner. Specifically, “Digital Proximity” does not merely provide a digital replica of the asset, but rather offers a digital-semantic model that enhances its interpretability through layered datasets capable of representing otherwise inaccessible aspects, such as subsurface structures, fragile materials, or historically stratified modifications. Through interactive visualization tools, parametric analyses, and semantic queries, stakeholders can conduct in-depth investigations, monitor changes over time, and simulate interventions without the constraints or risks associated with direct access. In this way, digital ecosystems redefine the concept of accessibility in heritage conservation, transforming remote interaction into a concrete analytical experience that supports planning, management, and preventive conservation.

Nevertheless, despite the growing dissemination of digital tools in the cultural heritage sector, the application of truly integrated approaches to low-accessibility contexts remains fragmented [6]. Access limitations hinder the continuity of data acquisition, verification, and updating processes, making systematic integration between surveying, analysis, and management difficult to achieve. Most existing research focuses on individual phases of the conservation process—such as geometric documentation, decay analysis, three-dimensional

visualization, or dissemination—without proposing structured and interoperable workflows capable of dynamically linking heterogeneous data, different scales of analysis, and multiple levels of fruition [12–14].

This highlights the need for replicable and interoperable methodologies capable of relating digital models, diagnostic data, and visualization environments within a single coherent workflow. The main objective is the definition and validation of an integrated methodological workflow for the knowledge, diagnosis, and management of low-accessibility architectural heritage, with particular reference to hypogeal sites characterized by complex geometries and multiple forms of inaccessibility (physical, related to risks for people and the asset, managerial, and cognitive).

This contribution aims to bridge the gap between physical inaccessibility and digital knowledge by structuring a scalable methodological system transferable to other contexts characterized by similar criticalities. The research proposes an approach oriented toward transforming traditional procedures into an interactive and adaptive knowledge system, in which data acquisition, semantic structuring, diagnostic interpretation, and visualization converge within immersive digital environments and web-based platforms. The expected results show how the systematic integration of these components can improve the continuity of the knowledge process, support decision-making, and reduce risk exposure in low-accessibility contexts.

This paper is organized as follows. Section 1 presents a systematic literature review on digital technologies and automation processes applied to low-accessibility architectural heritage. Section 2 introduces the proposed Methodological Workflow (MW), detailing the five main phases: Preliminary Knowledge and Multidisciplinary Data Structuring (PK–MDS), Comprehensive Digital Survey (CDS), Development of Integrated Digital Models (IDMs), Advanced Diagnosis and Monitoring (ADM), and the implementation of an Integrated Digital Environment for Hypogeal Heritage Management (IDE). Section 2 also illustrates the use of machine learning algorithms and diachronic analyses for decay mapping, as well as the architecture of integrated information systems and web navigation, with particular attention to interoperability between WebGIS and immersive environments. Section 3 illustrates the application of the methodology through the case study of the hypogeal rupestrian complex of San Pellegrino in Matera, combining a territorial-scale multi-site implementation with an in-depth site specific investigation to demonstrate the scalability, operational robustness, and multiscale applicability of the proposed workflow. Section 4 discusses the results obtained and the future perspectives of the research. Finally, Section 5 outlines the conclusions.

1.1. Literature Review

Scientific research on hypogeal and low-accessibility cultural heritage has undergone significant development in recent years, in parallel with the maturation of digital technologies applied to surveying, diagnosis, and management of historic built heritage [12,13,15]. In these contexts, inaccessibility is no longer interpreted exclusively as a physical barrier but emerges as a multidimensional condition resulting from the interaction between spatial constraints, structural fragility, risks to operator safety, managerial complexity, and limited availability of structured and updatable data [16]. The literature has progressively acknowledged digital technologies as playing a strategic role not only as representational tools but also as cognitive infrastructures capable of supporting articulated processes of documentation, preventive conservation, risk assessment, and controlled fruition of hypogeal heritage [17].

1.1.1. Digital Technologies for Hypogeal and Low-Accessibility Heritage

The integrated use of three-dimensional surveying techniques currently represents a consolidated reference for the documentation of hypogeal and underground contexts.

Numerous studies highlight how the combination of Terrestrial Laser Scanning (TLS) and Structure from Motion (SfM) photogrammetry enables the acquisition of dense and metrically reliable datasets, capable of recording geometry, surface texture, and conservation state with high accuracy, even in environments characterized by complex geometries, limited lighting conditions, and critical operational constraints [15,18–20]. In such contexts, point clouds assume the role of a foundational element of digital documentation, serving as a support for geometric analyses, dimensional assessments, and subsequent diagnostic elaborations.

At the same time, research has shown that three-dimensional surveying cannot be considered an objective in itself but must be integrated within frameworks oriented toward risk management and preventive maintenance. In this direction, the workflow proposed by Casarotto et al. [17] integrates 3D geometric documentation with diagnostic analyses and risk indicators, configuring a structured system for preventive maintenance planning in hypogeal archaeological sites. Similarly, Bartolini et al. in [10] demonstrate how the adoption of HBIM methodologies allows the integration of metric, diagnostic, and structural data within a single information environment, supporting structural diagnosis and informed management of historic built heritage.

A further line of research concerns the analysis of environmental conditions and degradation factors specific to underground contexts. Studies such as Corrao et al. [4], Luvidi et al. [21] and Frasca et al. [22] show how advanced surveying techniques can be employed to investigate complex phenomena such as microclimatic conditions and interactions between the natural environment and the built heritage, highlighting the role of digital surveying as a knowledge tool for understanding degradation mechanisms. Within this perspective, sustainable fruition has also been interpreted as a preventive conservation strategy, capable of reducing anthropogenic impact and contributing to the preservation of microclimatic equilibria [23].

1.1.2. Remote Fruition and Immersive Environments

Alongside developments oriented toward conservation and diagnosis, a substantial body of literature has focused on remote fruition as a response to the physical access limitations of hypogeal sites. In this context, web-based platforms for three-dimensional navigation represent one of the most widespread solutions for mitigating physical inaccessibility and promoting knowledge dissemination. Aricò et al. in [24] propose a web navigation system integrating 3D models with archaeological and interpretative content, demonstrating how remote access can enhance public understanding and awareness of otherwise inaccessible underground contexts. Similarly, Scianna et al. in [7], and Piscitelli in [8] highlight the role of web technologies and virtual tours in making inaccessible historic architectures accessible, emphasizing how such tools primarily contribute to heritage enhancement and communication. Within this line of research, Gaspari et al. in [9] propose an open-source web platform based on WebGL and Potree technologies for the documentation and storytelling of “hidden” cultural heritage, emphasizing the replicability and lightweight nature of digital solutions.

At the same time, Virtual Reality has assumed an increasingly relevant role in supporting fruition and technical knowledge of hypogeal heritage. Early studies have demonstrated how immersive VR environments can significantly enhance spatial and material understanding of physically inaccessible sites, supporting forms of cognitive and knowledge accessibility [25]. In this direction, Cantatore et al. in [26] propose a methodological

workflow based on spherical imagery and VR environments for representing the conservation state of a hypogeal site, highlighting the potential of such tools to reduce operator exposure to risk conditions and to support the sharing of technical information. A relevant contribution toward the integration of immersive environments and diagnostic data in historic architectural heritage is represented by the work of Gabellone and Masini in [27], who propose a platform based on VR/AR technologies for the contextualization and interpretation of non-invasive diagnostic data within immersive digital environments. The developed approach enables the integration of diagnostic information directly within the three-dimensional space of the architectural object, fostering an integrated reading of visible and invisible information and improving interpretative processes for both experts and non-specialist users. This contribution is positioned within the field of immersive environments as advanced tools supporting the knowledge and interpretation of built heritage, offering a solid methodological reference for the evolution of approaches oriented toward the progressive integration of data, processes, and levels of interpretation.

1.1.3. Automation and Artificial Intelligence in Decay Diagnosis

One of the main areas of development in recent research concerns the automation of decay diagnosis processes and the interpretation of three-dimensional data. The systematic review conducted by Sánchez-Aparicio et al. in [12] highlights how damage detection methodologies based on 3D data can be grouped into two main categories: geometry-oriented approaches, focused on analyzing morphological surface variations, and radiometry-oriented approaches, based on the analysis of chromatic and textural information. Within this context, photogrammetry has progressively extended its role beyond geometric documentation, becoming a tool for the semi-automatic interpretation of surface degradation phenomena. Galantucci et al. in [28] propose a machine learning pipeline for the segmentation and mapping of decay on 3D models, demonstrating the potential of such approaches to support objective and repeatable assessments of conservation state. Other studies introduce computer vision and deep learning models for the classification of defects and structural pathologies, achieving promising results but often strongly dependent on the application context [29]. In this direction, studies oriented toward point cloud segmentation as a support tool for knowledge and conservation processes of architectural heritage have also been developed. Nespeca et al. in [30] propose an advanced digital process based on automatic and semi-automatic point cloud segmentation techniques, aimed at analyzing the conservation state of historic buildings. The approach demonstrates how the processing and data mining of geometric and colorimetric information enable the identification of critical issues and degradation phenomena not immediately detectable through direct observation, contributing to a more informed and structured three-dimensional reading of historic built heritage.

From a similar perspective, but oriented toward the development of hybrid frameworks, Gbran et al. in [31] propose an approach combining deep learning techniques and three-dimensional analysis for adaptive segmentation and mapping of decay in historic structures. The contribution highlights the potential of integrating data-driven models with geometric information to support the interpretation of conservation state through repeatable and scalable procedures, reinforcing the role of automation as a tool supporting knowledge of built heritage. The use of convolutional neural networks for the semantic segmentation of historic surfaces is further explored by Vandenabeele et al. in [32] who demonstrate the effectiveness of such techniques in the automatic identification of morphological units and construction patterns on orthophotos derived from large-scale surveys. In parallel, the integration of diagnostic information within HBIM and GIS environments

enables the structuring of multiscale readings of built heritage, combining metric, historical, and material data within a single information system [14,33,34].

These developments suggest a progressive maturation of data-driven approaches, increasingly oriented toward flexible and transferable methodological structures, paving the way for the need for integrated workflows oriented toward continuous management.

1.1.4. Identification of the Research Gap and Positioning of the Study

Despite the richness and diversity of the contributions analyzed, the literature still reveals a fragmentation among the different phases of the conservation process. Many studies address individual aspects—such as geometric surveying, virtual fruition, automated diagnosis, or information management—through tools and platforms that often remain disconnected from one another. In particular, the literature shows that the systematic integration of multi-temporal monitoring, non-invasive diagnosis, and risk management within a single digital ecosystem still presents wide margins for development, especially in hypogeal and low-accessibility contexts.

Within this scenario, the present research is positioned as proposing a conceptual and methodological advancement through the transformation of the digital model from a predominantly representational tool into an integrated cognitive and operational system. The adopted approach aims to interconnect surveying, monitoring, diagnosis, and controlled fruition within an interoperable workflow, capable of continuously supporting processes of knowledge, interpretation, and monitoring oriented toward decision-making throughout the entire life cycle of low-accessibility cultural heritage.

2. Materials and Methods

2.1. The Methodological Workflow

This section describes the Methodological Workflow (MW) adopted for the development and validation of an Integrated Digital Environment (IDE) aimed at supporting the documentation, monitoring, and systemic management of hypogeal heritage (Figure 1).

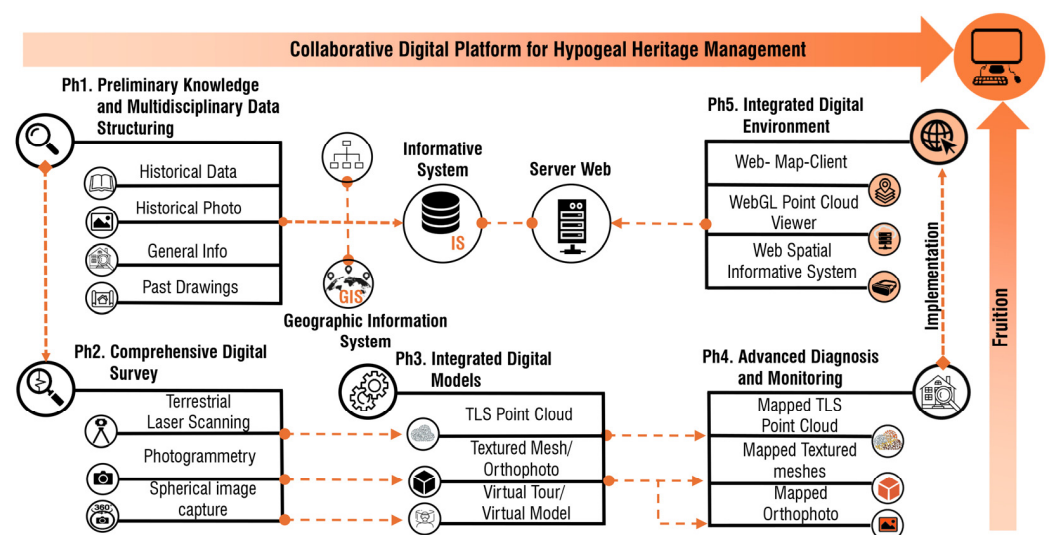


Figure 1. The Methodological Framework.

The proposed MW is articulated into five main phases:

Ph1. Preliminary Knowledge and Multidisciplinary Data Structuring (PK–MDS), focuses on collecting existing historical, architectural, and archaeological information and organizing it into an integrated framework.

Ph2. Comprehensive Digital Survey (CDS), involves the acquisition of high-resolution

geometric, colorimetric, and spatial data through advanced survey techniques.

Ph3. Development of Integrated Digital Models (IDMs), consists of creating coherent digital and semantic models that combine geometric, material, and descriptive information.

Ph4. Advanced Diagnosis and Monitoring (ADM), enables the analysis of conservative conditions and material degradation over time.

Ph5. Implementation of an Integrated Digital Environment for Hypogeal Heritage Management (IDE), establishes a collaborative digital platform that supports multi-user access, knowledge sharing, and conservation and management purposes.

Specifically, the proposed MW combines the potential of four main components: (i) information systems (e.g., relational databases) and GIS-based platforms, for the storage, organization, and structured management of the acquired data; (ii) image- and range-based models, together with Virtual Reality (VR) environments, which provide a comprehensive digital representation of the site and support analytical and evaluative processes; (iii) semi-automatic procedures enabling the supervised recognition of deterioration phenomena and the assessment of inaccessibility levels; and (iv) web-based approaches that ensure the integration, visualization, and dissemination of both digital models and associated informational content through a multi-level management of historical–constructive, technical, and inaccessibility-related information.

2.1.1. Preliminary Knowledge (PK) and Multidisciplinary Data Structuring (MDS)

The first phase of the MW establishes the preliminary knowledge framework required for the systematic documentation and management of hypogeal heritage (Figure 2).

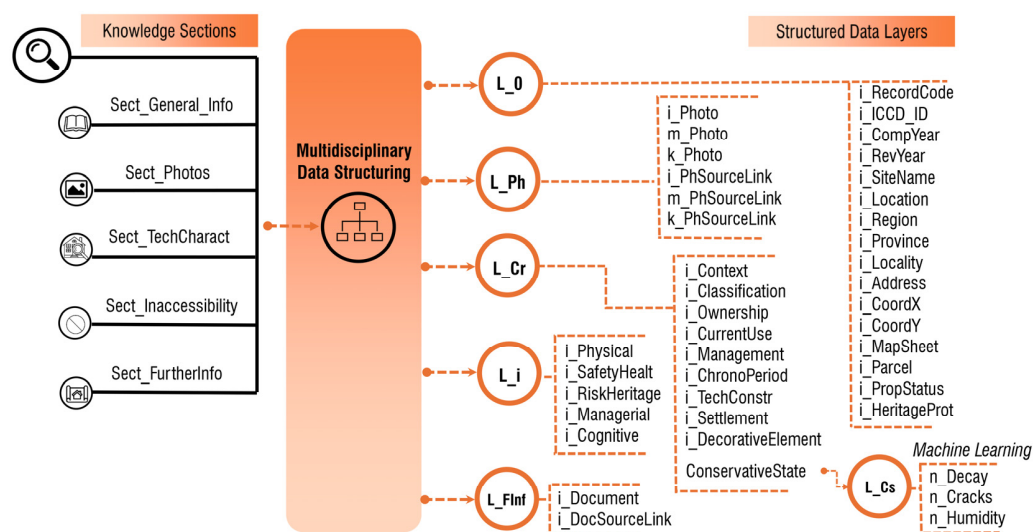


Figure 2. The Conceptual Model related to the structuring of Technical Knowledge.

This phase is primarily aimed at the development of an Information System (IS) capable of supporting the structured cataloguing of hypogeal sites and the assessment of their inaccessibility levels. Within this phase, particular emphasis is placed on the formalization and Structuring of Technical Knowledge (S_TK), which is achieved through the definition of a hierarchical, multi-level, and multidisciplinary conceptual model. This model is conceived to ensure semantic consistency, data interoperability, and informational coherence throughout all subsequent methodological and operational phases. The conceptual model provides a shared reference structure for the organization of heterogeneous data related to historical, architectural, geological, technological, and functional aspects of hypogeal heritage. It is articulated into five main sections, each corresponding to a specific thematic domain, and collectively defining the logical structure of the database. Data originating

from heterogeneous source, including archival materials (textual documentation, historical photographs, and technical drawings), direct survey outputs (point clouds, photographic datasets, and spherical imagery), and territorial information systems (orthophotos and official cartography), are systematically acquired, harmonized, and organized within the relational database according to the conceptual model. The data collection process is supported by both manual and automated procedures, ensuring consistency, traceability, and repeatability.

Table 1. Implementation of the reference conceptual model attributes across the different digital models and their availability within the unified information system, general attributes (descriptive information, photo).

Attributes	Implementation of Semantic Data in the Digital System/Model				
	IS	GIS	TLS_Cloud	VT	VM
i_RecordCode	Text	Text	Sheet (.pdf)	Sheet (.pdf)	
i_ICCD_ID	Text	Text	Sheet (.pdf)	Sheet (.pdf)	
i_CompYear	Integer	Integer	Sheet (.pdf)	Sheet (.pdf)	
i_RevYear	Integer	Integer	Sheet (.pdf)	Sheet (.pdf)	
i_SiteName	Text	Text	Sheet (.pdf)	Sheet (.pdf)	
i_Location	Text	Text	Sheet (.pdf)	Sheet (.pdf)	
i_Region	Text	Text	Sheet (.pdf)	Sheet (.pdf)	
i_Province	Text	Text	Sheet (.pdf)	Sheet (.pdf)	
i_Locality	Text	Text	Sheet (.pdf)	Sheet (.pdf)	
i_Address	Text	Text	Sheet (.pdf)	Sheet (.pdf)	
i_CoordX	Geometry (Point)	Geometry (Point, .shp)	Sheet (.pdf)	Sheet (.pdf)	
i_CoordY	Geometry (Point)	Geometry (Point, .shp)	Sheet (.pdf)	Sheet (.pdf)	
i_MapSheet	Integer	Integer	Sheet (.pdf)	Sheet (.pdf)	
i_Parcel	Integer	Integer	Sheet (.pdf)	Sheet (.pdf)	
i_PropStatus	Text	Text	Sheet (.pdf)	Sheet (.pdf)	
i_Heritage Prot	Text	Text	Sheet (.pdf)	Sheet (.pdf)	
i_nPhoto	Image (.jpeg, .png, .tif)	Image (.jpeg, .png, .tif)	Sheet (.pdf)	Sheet (.pdf)	
i_nPhSource Link	Text (URL)	Text (URL)	Sheet (.pdf)	Sheet (.pdf)	

This organization supports the standardized acquisition, validation, and management of multidisciplinary information, while enabling automated data collection procedures and minimizing inconsistencies typically associated with fragmented documentation practices. This approach enables the consistent and centralized recording of all descriptive attributes, construction techniques, conservation states, and accessibility parameters, ensuring their uniform integration across each prepared digital system and model. Tables 1 and 2 provide a comprehensive overview of the attributes defined in the reference conceptual model and illustrate how they are implemented and made accessible within the various digital systems and models.

Within the PK–MDS phase, hypogeal sites are systematically catalogued and classified using defined digital forms derived from the conceptual model. The structured information is subsequently integrated within a GIS-Based System (Geographic Information System),

enabling the georeferencing of each site and the association of alphanumeric attributes with spatial entities. By establishing a coherent and scalable data structure at an early stage, the PK–MDS phase provides a robust foundation for advanced analyses, digital modelling and monitoring activities addressed in the subsequent phases of the MW.

Table 2. Implementation of the reference conceptual model attributes across the different digital models and their availability within the unified information system, including technical attributes (descriptive information, conservation state, accessibility parameters).

Attributes	Implementation of Semantic Data in the Digital System/Model				
	IS	GIS	TLS_Cloud	VT	VM
i_Context	Text	Text	Sheet (.pdf)		Sheet (.pdf)
i_Classification	Text	Text	Sheet (.pdf)		Sheet (.pdf)
i_Ownership	Text	Text	Sheet (.pdf)		Sheet (.pdf)
i_CurrentUse	Text	Text	Sheet (.pdf)		Sheet (.pdf)
i_Managment	Text	Text	Sheet (.pdf)		Sheet (.pdf)
i_ChronoPeriod	Text	Text	Sheet (.pdf)		Sheet (.pdf)
i_TechConstr	Text	Text	Sheet (.pdf)		Sheet (.pdf)
i_Settlement	Text	Text	Sheet (.pdf)		Sheet (.pdf)
i_Decorative Element	Text	Text	Sheet (.pdf)		Sheet (.pdf)
ConservativeState	Text	Text	TLS_mapped_cloud (.LAS, .E57, .ply, .pts)	TLS_map_plt (.LAS, .E57, .ply, .pts) Map_Orthoph (.jpeg)	Map_Orthoph (.jpeg) Map_txt (.obj, .ply, .fbx, .gltf, .glb)
i_Physical	Text	Text	Sheet (.pdf)		Sheet (.pdf)
i_SafetyHealt	Text	Text	Sheet (.pdf)		Sheet (.pdf)
i_RiskHeritage	Text	Text	Sheet (.pdf)		Sheet (.pdf)
i_Managerial	Text	Text	Sheet (.pdf)		Sheet (.pdf)
i_Cognitive	Text	Text	Sheet (.pdf)		Sheet (.pdf)
i_Document	Text	Text	Sheet (.pdf)		Sheet (.pdf)
i_DocSourceLink	Text (URL)	Text (URL)	Sheet (.pdf)		Sheet (.pdf)

2.1.2. Comprehensive Digital Survey (CDS)

Following the first phase, a comprehensive digital survey is conducted to acquire high-resolution geometric and visual information from the hypogeal sites.

Within this framework, the survey integrates multiple acquisition techniques, including photogrammetry, Terrestrial Laser Scanning (TLS), and spherical image capture, ensuring a robust and comprehensive digital documentation of the hypogeal heritage.

This phase is preceded by the definition of a structured Survey Plan (SP), corresponding to the pre-operative stage of architectural digitalization and informed by historical, archival, and documentary sources. Based on this preliminary knowledge, technical experts design the acquisition strategy by defining the positioning of spherical cameras and laser scanner stations, and the overall number of images, in accordance with the morphological characteristics of the built environment (e.g., number, size, and spatial configuration of rooms, as well as feature of decorative details). This planning activity is essential to guarantee adequate overlap between spherical images and laser scanner stations, and to maximize the completeness of data capture. The SP also accounts for varying levels of accessibility, combining complementary operational approaches: the use of tripods for easily or partially

accessible spaces, and robotic systems or Unmanned Aerial Vehicles (UAVs) for areas that are difficult or impossible to reach. Furthermore, each technique contributes distinct and complementary types of information to the survey process. Photogrammetry supports the acquisition of high-resolution textured surfaces and colorimetric attributes, while TLS technique guarantees accurate metric measurements and the reliable reconstruction of three-dimensional geometries. Spherical image survey, in turn, records immersive visual environments and spatial relationships that are only partially captured by conventional surveying methods. The integrated application of these techniques enables the development of comprehensive digital models capable of preserving both fine-grained morphological features and the overall spatial organization of the surveyed sites.

2.1.3. Integrated Digital Models (IDMs)

The third phase focuses on the development of Integrated Digital Models (IDMs), conceived as a unifying framework enabling structured interaction among metric entities, virtual environments, and spatial-informative systems. In IDMs phase, all survey-derived datasets undergo systematic processing and rigorous quality control procedures, including noise reduction, dataset alignment, and validation of metric reliability. These operations ensure the geometric coherence and accuracy required for subsequent procedures. A central role in this phase is played by the processing of photogrammetric (RGB_Mesh), Terrestrial Laser Scanning (TLS_Cloud) and spherical (Shp_image) data, which together constitute the metric and colorimetric database of the integrated digital environment. Photogrammetric surveys are processed enabling the generation of high-resolution colorimetric point clouds (RGB_Point Cloud), textured meshes (RGB_Mesh) and orthoimages. In parallel, TLS_Cloud datasets are processed to produce dense colorimetric and metrically reliable point clouds, ensuring precise geometric measurements and the accurate reconstruction of spatial configurations, even in complex or low-light hypogeal environments. These approaches (image- and range-based) allow the detailed documentation of material characteristics and surface conditions, which are essential for conservation assessment and decay analysis. Complementarily, Integrated Virtual Environments (IVE), including Virtual Tours (VTs) and Virtual Models (VMs) support immersive and semi-immersive representations of the environments, enhancing both technical interpretation and dissemination (Figure 3).

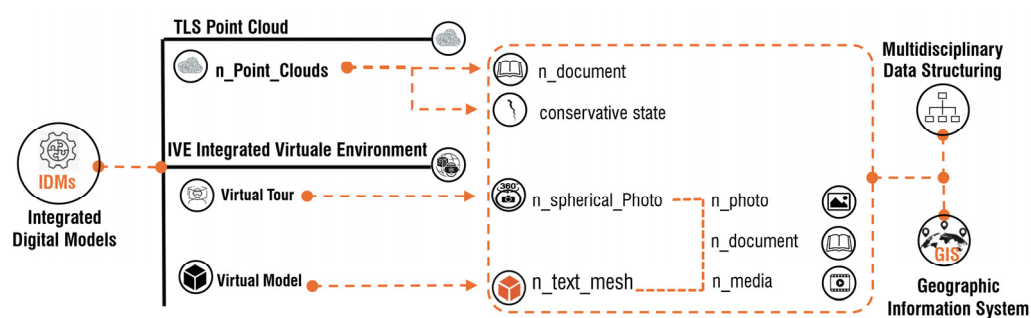


Figure 3. Schematic representation of the Integrated Digital Models (IDMs) development process (© Authors).

Specifically, the development of VTs follows a complementary, image-based workflow centered on the processing of Shp_images datasets. Initially, the n Shp_images acquired are spatially organized and linked according to the predefined acquisition plan, preserving correct spatial relationships and viewpoints, as well as to ensure visual continuity and coherence across different acquisition points. Interactive navigation paths are defined by linking adjacent Shp_images through hotspots, allowing seamless transitions and intuitive exploration of the environments. Meanwhile, VMs are generated through the integration of textured meshes derived from RGB_Mesh data. In a subsequent step, VTs and VMs are

structured according to predefined hierarchical and semantic criteria, defined during the PK–MDS phase, enabling the association of geometric elements with descriptive attributes, diagnostic information, and thematic layers stored within the IS. This process produces interactive virtual models capable of supporting both metric interrogation and thematic visualization, guaranteeing semantic coherence and seamless interoperability with the IS and the GIS-Based System. Together, VMs and VTs constitute interoperable components of the IDMs, combining metric accuracy, immersive visualization, and semantic enrichment. Their coordinated use supports expert analyses, facilitates remote inspection and monitoring, and enhances dissemination and decision-making processes, particularly in the context of complex and fragile hypogeal heritage environments. The Integrated Digital Environment, developed according to user-centered design approaches, incorporates performance and usability criteria derived from established frameworks that have already been validated by the authors in analogous applications [35].

2.1.4. Advanced Diagnosis and Monitoring (ADM)

The fourth phase is dedicated to the systematic assessment of the conservation state of hypogeal heritage. This phase is grounded in the continuous observation and analysis of decay phenomena through semi-automated mapping processes, integrating segmentation procedures, supervised classification approaches, and quantitative assessment methods (Figure 4). The ADM phase adopts a multi-scale analytical strategy, structured across complementary levels of investigation that respond to different spatial resolutions and conservation needs. Each level is supported by specific digital representations and tailored diagnosis procedures, enabling both the large-scale interpretation of decay patterns and the detailed investigation of material-sensitive components. In this context, analytical methods are used to ensure diachronic monitoring strategies that allow for repeatability, objectivity and comparability of results over time.



Figure 4. Subphases of the semi-automatic processes for decay mapping: on the left, site scale; on the right, detailed scale (© Authors).

Decay Mapping at the Site Scale

This sub-phase focuses on the analysis of architectural surfaces through the processing of range-based spatial datasets (TLS_Cloud) for the comprehensive assessment of the conservation state of hypogeal sites. Specifically, the level of investigation supports the identification, classification, and spatial distribution of the main decay patterns affecting hypogeal environments. To facilitate a controlled and interpretable assessment, the spatial dataset is preliminarily subdivided into discrete subsets, each corresponding to a specific environmental context within the hypogeal site.

This geometry-based segmentation reduces analytical complexity by subdividing the spatial dataset into homogeneous units defined by morphological coherence. Such

partitioning enables the targeted analysis of surface conditions within individual environments, enhancing the interpretability of decay patterns and supporting more reliable comparative assessments across spatial subsets. For each spatial subset (i TLS_cloud), a semi-automated decay mapping procedure is applied, based on the analysis of chromatic attributes (RGB value).

The adopted supervised classification strategies, supported by domain-specific expertise, guide the identification and categorization of surface alteration patterns, resulting in a mapped point cloud (Map_TLS_cloud). Within this process, Machine Learning algorithms play a key role in enhancing the consistency and scalability of decay mapping, allowing for the systematic recognition of recurring alteration features while maintaining interpretative control by conservation specialists. Furthermore, the methodological procedure is structured as a scalable and repeatable framework for the diachronic monitoring of deterioration processes based on the comparison of multi-temporal spatial datasets.

Diachronic Analysis of Decorative Elements

At the detail scale, the diagnosis process focuses on decorative apparatuses and material-sensitive elements, such as frescoes, painted surfaces, and stucco components, which require higher levels of chromatic resolution. This level of investigation relies on the integrated analysis of high-resolution images, orthophotos, and textured surface models. These representations form the basis for the application of semi-automated analytical procedures aimed at detecting and quantifying material, chromatic, and surface alterations. In particular, Machine Learning-based methods are employed to support the segmentation and classification of areas affected by material loss, colorimetric variations, surface deposits, or detachment of pictorial layers. This semi-automatic procedure results orthophotos (Map_Ortho) and textured meshes (Map_RGB_Mesh), both mapped.

The methodological framework is further strengthened through diachronic comparison, integrating contemporary datasets with historical iconographic documentation to reconstruct the temporal evolution of decorative and material conditions. By systematically comparing multi-temporal and multi-source representations, this approach enables the monitoring of deterioration trajectories and the identification of critical changes. As a result, the detail-scale investigation provides a robust, repeatable, and evidence-based framework for tracking conservation dynamics affecting decorated and architecturally significant surfaces, enhancing long-term monitoring and preventive conservation decision-making.

2.1.5. Integrated Digital Environment for Hypogeal Heritage Management

The final phase regards the development a web-based collaborative digital platform to support the integrated management of hypogeal heritage, enabling the centralized organization, visualization, and sharing of heterogeneous spatial and descriptive data. Within this framework, spatial datasets and diagnosis information are structured within a relational data environment designed following the same structure of defined conceptual model. This configuration facilitates the coordinated management of geometric, semantic, and diagnostic information, supporting collaborative workflows among different stakeholders involved in conservation and site management. To enable efficient online visualization and interaction with high-density spatial data, the MW incorporates multi-resolution data structures and hierarchical representations, allowing complex three-dimensional datasets to be accessed and explored through standard web interfaces. The collaborative platform is conceived as an integrated digital system in which multiple elaborated digital models (spatial databases, georeferenced information layers, three-dimensional models, and immersive visualization environments) are interconnected within a unified informative system. Hierarchical navigation mechanisms and interactive access points enable users to

move across different levels of detail and information domains, linking spatial elements to structured records, diagnostic results, and historical documentation. This interconnected architecture supports cross-referencing, traceability of information, and continuous updating of data, enhancing transparency and coordination in decision-making processes. Overall, the MW establishes a collaborative and extensible digital environment for hypogeal heritage management, promoting data sharing and interdisciplinary cooperation. By enabling synchronized access to updated diagnostic, spatial, and descriptive information, the platform supports long-term monitoring, preventive conservation strategies, and adaptive management of complex hypogeal heritage sites.

3. Results

This section presents the application and validation of the proposed MW through a two-tiered, multiscale strategy that integrates a territorial-scale implementation with an in-depth site-specific investigation. In coherence with the systemic and heterogeneous nature of hypogeal heritage outlined in the previous sections, this approach is intended to evaluate both the scalability of the workflow across multiple contexts and its operational effectiveness at the individual site scale.

3.1. Multi-Site Implementation of the Knowledge Structuring Phase

The initial phase of the methodology, focused on knowledge structuring and classification, was applied on a representative sample of 66 religious hypogeal sites, including crypts, sanctuaries, and rock-cut caves, distributed across the Apulia and Basilicata regions in southern Italy (Figure 5).

The selected dataset reflects both the historical and cultural significance of hypogeal heritage and the heterogeneity of morphological configurations, spatial layouts, and functional typologies, providing a robust testbed for the application of the methodological framework at a regional scale. In accordance with the PK phase, the 66 hypogeal sites were systematically catalogued and classified following a predefined conceptual model (Section 2.1.1). Data collection was carried out by technical experts using a structured Google Form designed to ensure consistency and completeness of the acquired information.

The collected data were automatically stored in a Google Sheets database, which enabled centralized management, validation, and updating of the records. Through the Autocrat add-on for Google Sheets, defined cataloguing sheets were automatically generated in textual formats (DOCX and PDF), ensuring traceability between the original digital entries and the derived documentation. The catalogued dataset was subsequently integrated into a GIS-Based System, implemented using QGIS software (version 3.38.3), allowing the georeferencing of each hypogeal site, in the global reference system (WGS84-UTM 33N), and the enrichment of spatial layers with alphanumeric attributes derived from the cataloguing process. Within this environment, each hypogeal site was georeferenced as a point feature, using the geographic information recorded in the corresponding cataloguing forms. The point-based spatial representation enabled the precise localization of each site within a unified coordinate reference system, ensuring spatial consistency across the dataset. The GIS-Based System was structured through the creation of dedicated vector layers, in which each point feature was associated with a comprehensive attribute table populated with the alphanumeric data derived from the cataloguing process. These attributes include descriptive, typological, chronological, and conservation-related information, as well as references to diagnostic results and linked digital resources.

Moreover, to support advanced data management and interoperability, the GIS environment was connected to a PostgreSQL relational database extended with PostGIS, providing robust storage and querying capabilities for both spatial and non-spatial

data. Database management and maintenance were carried out through the pgAdmin 4 (version 4.30) graphical interface.

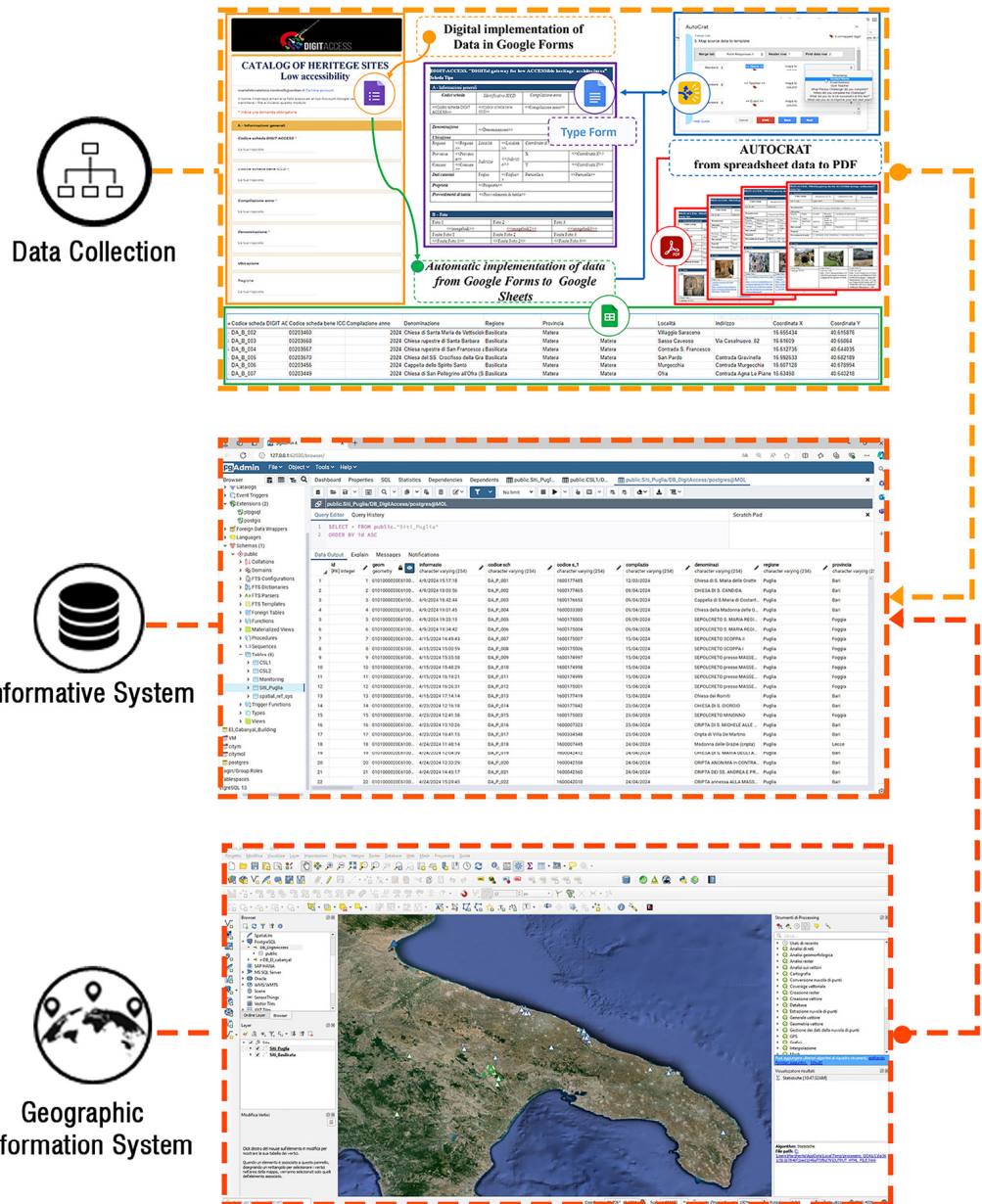


Figure 5. The workflow for the survey and management of hypogean sites (© Authors).

3.2. Methodological Workflow Applied to the San Pellegrino Rupestrian Complex

For reasons of conciseness, this section focuses on the application and validation of the MW phases at the hypogean site scale, as implemented in the case study of the San Pellegrino Rupestrian Complex (Figure 6). Specifically, all phases of the approach, from multi-source data acquisition and integrated digital survey to semantic structuring, conservation assessment, and web-oriented fruition, were systematically applied within a unified operational framework. Owing to its morphological complexity, stratified development, and critical conservation conditions, the rupestrian complex constituted a particularly suitable case study for testing the robustness and applicability of the MW.



Figure 6. View of the San Pellegrino rupestrian complex in the Ofra area, Matera, Basilicata (Southern Italy) (© Authors).

3.2.1. Historical Context

The San Pellegrino rupestrian complex at Ofra is located within a landscape of extraordinary morphological complexity and historical stratification. Approximately five kilometers northwest of Matera, the site develops along a deeply incised slope, characterized by rocky outcrops, steep gradients, and marked lithological discontinuities, in an area that has favored human settlement since the earliest phases, thanks to the combined presence of natural cavities suitable for shelter functions and the proximity of the Gravina stream, a strategic water resource. From a morphological and spatial perspective, the San Pellegrino rupestrian complex can be described as an articulated and highly adaptive hypogeal system, directly excavated into the rock mass and profoundly transformed over the centuries in response to highly critical geomorphological and structural conditions. The settlement develops along a steep escarpment characterized by heterogeneous lithology, marked by the transition from compact limestone layers to more friable calcarenite strata, a condition that has significantly affected the overall stability of the site. This lithological discontinuity represents a determining factor in the instability phenomena that define the site as a high-risk environment in terms of safety and severely limit the possibilities for direct inspection. The rock face is affected by a widespread state of fracturing and structural degradation phenomena that, over time, have led to significant collapses of external walkways and original connection paths. These events have produced profound morphological and functional modifications of the rupestrian layout, requiring the creation of new internal connections through the excavation of narrow, inclined, and irregularly developed corridors, conceived as adaptive solutions replacing the collapsed external routes. As a result, the internal spaces do not follow regular geometries but are articulated in a complex sequence of interconnected rooms, narrow passages, niches, arcosolia, and circulation paths at different elevations, with marked variations in height, depth, and natural lighting conditions.

From the perspective of spatial and functional organization, the rupestrian settlement is articulated into three main sectors, originally connected by stairways carved directly into the rock escarpment, which are now largely destroyed or rendered impracticable by collapses that occurred over time. This articulation reflects a stratified functional distribution, in which productive, cultic, and service spaces coexist within a unitary yet morphologically complex system. The first sector, known as *“Pecchiara a monte,”* consists of a cavity delimited by a robust dry-stone wall, historically used for beekeeping. The intermediate sector, configured as a transitional area between productive functions and more strictly residential ones, is characterized by terraces carved into the limestone bedrock and niches excavated for the placement of beehives. In this sector, the presence of a boundary cross is documented, an element of particular historical interest related to land demarcation practices. The third sector, corresponding to the core of the San Pellegrino

complex, represents the most articulated portion of the settlement and develops over three superimposed levels, connected by adaptive internal paths, forming a system that accommodates the rupestrian church at the intermediate level and a series of spaces intended for productive, service, and funerary functions.

The progressive abandonment of the area and the loss of traditional maintenance practices have contributed to transforming San Pellegrino into an environment characterized by low physical accessibility, high risks for the conservation of the asset and for human safety, and a limited possibility of direct inspection. It is precisely this combination of value, complexity, and fragility that makes San Pellegrino a paradigmatic case study of low-accessibility hypogeal sites. The site is the subject of ICCD (Central Institute for the Catalogue and Documentation, Italian Ministry of Culture) cataloguing, carried out in 2020 and registered in the General Catalogue of Cultural Heritage, with an indication of the framework of constraints: the asset has been under state protection by ministerial decree (DM) since 14 February 1969 (Law no. 1497/1939 and Law no. 1089/1939), as well as under regional provisions (Law 11/90). The ICCD documentation also refers to plan and section drawings of the church dated January 1989.

The presence of lithic finds attributable to the Neolithic period, discovered in the Ofra area, attests to an early occupation of the territory, linked to the exploitation of natural resources and the geomorphological configuration of the site. This long continuity of occupation confers upon the complex a stratigraphic and symbolic value that precedes and prepares the development of the medieval rupestrian settlement.

The phase of greatest structuring of the site can be attributed to the medieval period, when the complex acquired a clear religious connotation.

The rupestrian Church of San Pellegrino, excavated directly into the rock mass, represents the architectural, symbolic, and functional core of the entire complex, set within a territorial context characterized by the presence of approximately 150 rupestrian cult architectures recorded in the Matera area, one of the most significant concentrations of hypogeal places of worship in southern Italy (Figure 7a). Around the church, an articulated system of secondary hypogeal spaces progressively developed, testifying to a prolonged and adaptive use of the site over time.



Figure 7. San Pellegrino Ofra rupestrian complex: (a) overall layout of the complex; (b) hypogeal rupestrian chamber; (c) articulation of circulation paths along the rocky escarpment; (d) 13th-century wall paintings depicting a bishop Saint (© Authors).

The presence of a rupestrian burial area, directly connected to the cult spaces, further reinforces the sacred value of the complex, documenting funerary practices and rituals that attributed to this place a symbolic mediating function between the world of the living and that of the dead. Church and burial area thus constitute an architectural and symbolic *unicum*, expressing a conception of sacred space deeply rooted in the rupestrian

landscape. The church itself is configured as a natural cavity of considerable dimensions, excavated and progressively reworked between the 11th and 13th centuries. The space presents an irregular morphology, with a highly articulated ceiling affected by widespread fracturing, while the original floor level has been profoundly altered as a result of successive lowering operations that led to the loss of original architectural and liturgical elements. The configuration of the entrance underwent significant transformations following collapses that occurred in the late medieval period: the original access, presumably aligned with the apsidal axis, collapsed in the 15th century and was replaced by a blocking wall bearing a red-painted cruciform motif. Above the entrance, a hole used in the past for smoke exhaust is also recognizable, indicating subsequent refunctionalizations of the space. From the perspective of internal organization, the apsidal bay preserves a niche with a round arch, while the original altar and sacred furnishings are no longer present. The rupestrian burial area, directly connected to the church, is configured as a quadrangular funerary space excavated into the rock, originally articulated into arcosolia intended for burials.

Over time, functional transformations of the complex have modified the original spatial layout: one arcosolium was demolished to create an internal connection, while the others were reused during pastoral use phases. Nevertheless, the space retains sufficient spatial legibility to recognize its original function and structural role within the overall organization of the rupestrian complex (Figure 7b,c).

During the 18th century, under the ownership of the Venusio family, the complex underwent a significant change in use, shifting from an apiary to a shelter for sheep and goats, a function maintained until the mid-20th century. This transformation involved a series of structural and material modifications, including the lowering of floor levels, sometimes accompanied by the extraction of stone blocks, and the widespread blackening of surfaces due to prolonged use of hearths and the presence of animals. The masonry surfaces of the church also preserve recesses for wooden beams indicating the subdivision of the space into two levels, as well as a cistern and a basin for straw, elements that explicitly document the use of the sacred building as a stable in the modern period.

Within the rupestrian Church of San Pellegrino, significant pictorial decorations are preserved, attributable to different decorative and devotional phases spanning from the 12th–13th century to the 19th century. Although currently in a fragmentary state, the wall paintings testify to the long continuity of use of the sacred space and its progressive re-signification over time. Among the earliest testimonies are the remains of a fresco depicting a Bishop Saint, located on the right wall of the nave and today preserved only in its lower portion (Figure 7d). The work, attributable to the 13th century, is traditionally referred to Saint Nicholas, although the absence of unambiguous iconographic attributes does not allow for a certain identification [36].

A later decorative phase is documented by the fresco of the Madonna and Child with Saints, dated to 1839, located within a wide and shallow niche on the left wall, probably obtained from a re-adapted funerary arcosolium.

The presence of a dedicatory inscription along the lunette allows for a precise dating of the intervention and attests to the persistence of devotional practices even during an advanced phase of functional transformation of the site.

3.2.2. Detailed Diagnosis and Monitoring Workflow for a Representative Hypogeal Site

Starting from the analysis of the preliminary documentation and an assessment of site accessibility and environmental constraints, the most suitable survey strategies, acquisition techniques, and digital tools were selected to ensure accurate and reliable documentation of the hypogeal complex.

The acquisition protocol was designed according to principles of operational flexibility and radiometric control, in order to ensure consistent and reliable documentation conditions. The photogrammetric survey was planned to achieve an average Ground Sampling Distance (GSD) of approximately 0.4 mm/pixel, calculated based on the camera sensor characteristics, focal length, and the average distance between the camera and the surveyed surfaces. Image acquisition was performed using the integrated camera system of a Samsung Galaxy S21 Ultra smartphone, equipped with a 108 MP wide-angle sensor (1/1.33" CMOS), an equivalent focal length of 26 mm, and an aperture of $f/1.8$, enabling the capture of high-resolution imagery suitable for detailed surface reconstruction.

Given the limited accessibility and the absence of fixed electrical infrastructure in the underground environments investigated, illumination conditions were carefully controlled through the use of lightweight, battery-powered LED lighting systems with a controlled color temperature of approximately 5000–5600 K. This configuration ensured uniform illumination and radiometric stability, reducing shadows and color inconsistencies and supporting the acquisition of photogrammetric datasets suitable for accurate geometric reconstruction and reliable visual documentation. Images were captured in high-resolution mode to maximize surface detail and ensure adequate overlap between consecutive frames. Metric consistency was ensured by aligning the photogrammetric model with the reference point cloud derived from Terrestrial Laser Scanning (TLS) surveys.

The collected image datasets were processed using Structure from Motion (SfM) algorithms implemented in Agisoft Metashape Professional (version 1.5.2), resulting in detailed image-based 3D models.

These outputs include dense point clouds, high-resolution textured polygonal meshes, orthorectified images, and texture maps, providing a comprehensive and colorimetric reliable representation of the decorated surfaces (Figure 9).

In parallel, the IVE have been elaborated using 3DVista Virtual Tour software (version 2026.0.5).

On the one hand, the spherical images acquired during the survey TLS campaign were interconnected, following the survey plan, to develop a navigable VT. On the other hand, the image-based 3D model was employed as the foundation for the VM of the hypogean site.

Concurrently, the VTs and VMs were interconnected and semantically enriched through real-time texture rendering and the integration of informative overlays, including interactive hotspots linking to decay-mapped datasets, alphanumeric metadata, and historical and technical documentation. The semantic content of the IVE was enhanced through the implementation of customized hotspots designed as access nodes to heterogeneous datasets and analytical resources.

These elements provide direct connections to processed three-dimensional models, such as point clouds, textured meshes, and orthophotos, as well as to diagnostic outputs, analytical systems, and associated descriptive and archival information. This integrated configuration enables seamless transitions between immersive spatial navigation and the consultation of detailed technical information across multiple levels of detail.

To support efficient visualization and interaction, the IVE was structured using hierarchical data organization and multi-resolution strategies, in accordance with the adopted conceptual model (Figure 10).

In line with the MW, the ADM phase was implemented to test and validate semi-automatic monitoring procedures aimed at assessing the conservation state at two complementary scales of analysis, namely the site scale and the detail scale.

At the site scale, the analysis focused on the overall conservation condition of the hypogean complex, primarily exploiting the range-based point clouds generated during the previous IDM phase.



Figure 9. Digital photogrammetry output for the study area: detailed view of the dense point cloud (RGB_Point Cloud), the textured mesh (RGB_Mesh), and the resulting orthoimage, illustrating the geometric and radiometric restitution of the surveyed surfaces (© Authors).

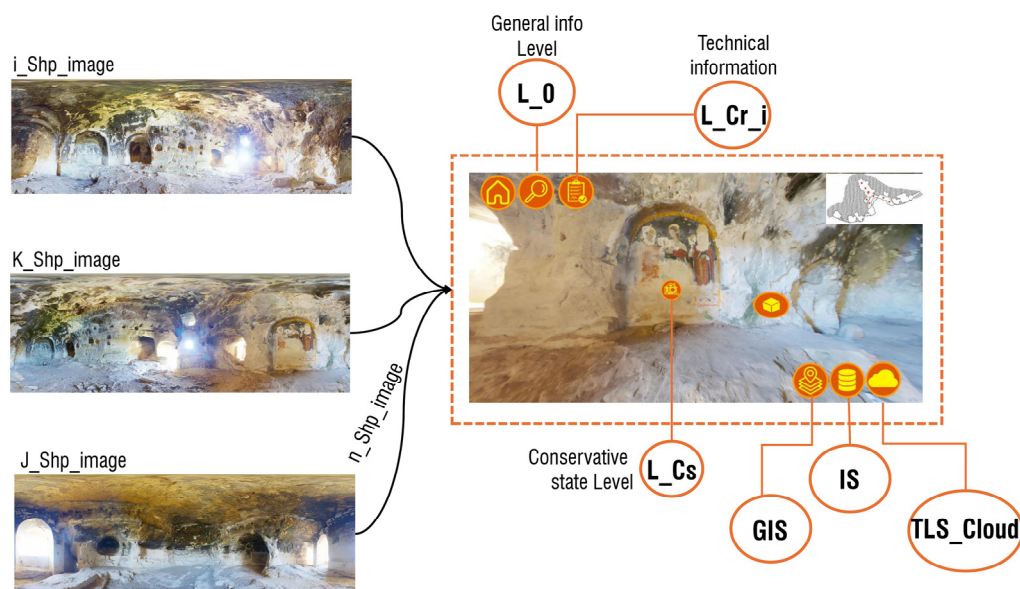


Figure 10. Virtual Tour (VT) development through the integration of spherical images and interactive hotspots (© Authors).

Prior to the execution of the decay detection procedures, the global point cloud was segmented into discrete subsets, each corresponding to a specific hypogeal environment, in order to improve data manageability and the accuracy of the results.

This segmentation process was carried out through a manual procedure using Autodesk ReCap Pro (version 5.0.0.40), allowing each point cloud subset to be associated

with a distinct spatial unit. Subsequently, for each environment represented as a child range-based point cloud (i TLS_cloud), a semi-automatic, point-based mapping of decay phenomena was performed using the Colorimetric Segmenter plugin within the CloudCompare software (version 2.12.4) environment.

The decay detection, segmentation and classification process was guided by expert knowledge, ensuring the interpretative validation of the automatically extracted results. Specifically, these datasets were processed to identify chromatic anomalies affecting wall and vault surfaces, which were associated with decay through the expert interpretation of the specialist responsible for the identification and classification phase. Through an iterative calibration of colorimetric parameters, a set of RGB threshold values was defined to support the semi-automatic detection of areas affected by surface decay, with particular reference to biological colonization and superficial deposits (Figure 11).

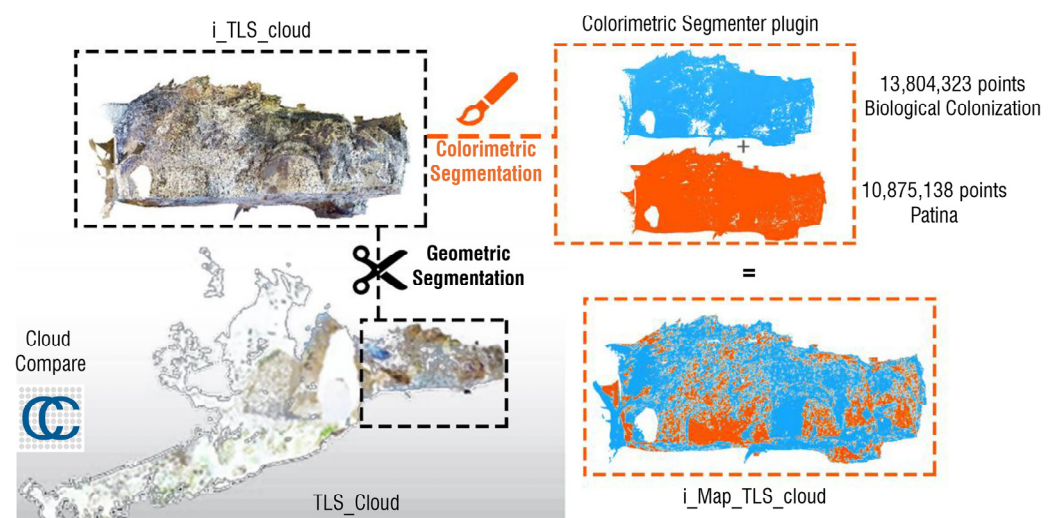


Figure 11. Semi-automatic detection of surface decay on i_TLS_cloud using the Colorimetric Segmenter plugin implemented in CloudCompare (© Authors).

Consequently, the classified and segmented portion of the i TLS_cloud was associated with a single scalar color between 1 (black) and 255 (white) corresponding to the degradation type (i Map_TLS_cloud) (Convert to Scalar Field has been used in CloudCompare).

In parallel, the conservation monitoring of the fresco located within the religious hypogeal site was conducted with the aim of quantifying and precisely localizing areas of material loss affecting the decorative surfaces.

This investigation was performed through a diachronic analysis of a historical black-and-white photograph dating to 1976 ($t - 1$) and a high-resolution orthoimage (t_0) derived from the three-dimensional digital model obtained via image-based photogrammetric techniques. Specifically, the historical image was processed in TriDMetriX through a planar projective transformation, followed by the definition of the metric scale, resulting in an orthorectified image suitable for the diachronic analysis of degraded surfaces.

The mapping of loss areas on the fresco was subsequently conducted through a supervised image segmentation procedure, applied in parallel to both the historical black-and-white photograph and the elaborated high-resolution orthoimage.

The segmentation workflow was based on a Random Forest classifier implemented within the Trainable Weka Segmentation plugin of Fiji (ImageJ) (version 1.54p, Wayne Rasband and contributors National Institutes of Health, USA) (Figure 12). This approach involved several key steps to ensure accuracy and reproducibility. First, representative training Regions Of Interest (ROIs) were manually selected, distinguishing areas corresponding to intact surfaces and material loss.

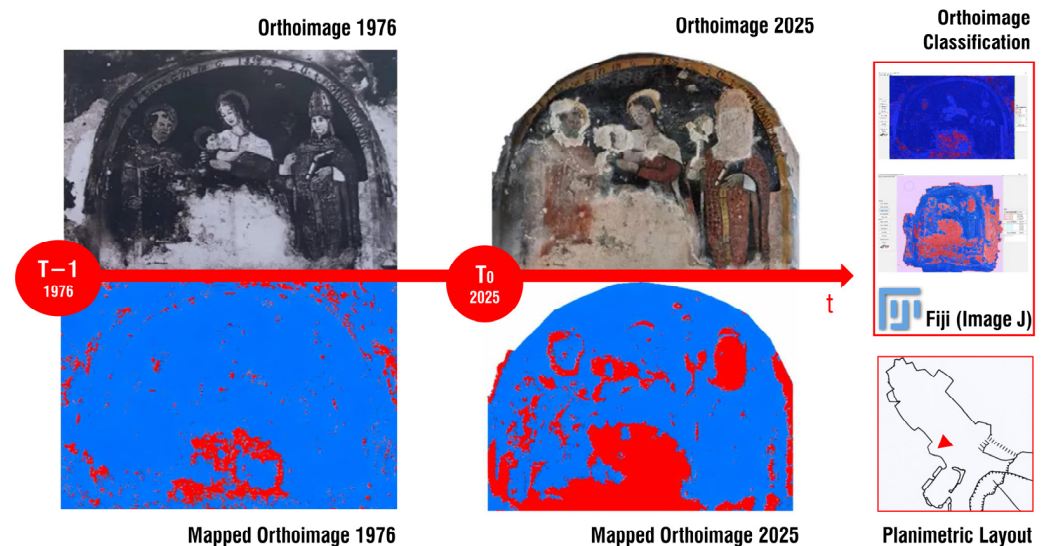


Figure 12. Conservation monitoring of the fresco surface through diachronic comparison between a 1976 historical photograph ($t - 1$) and a recent orthoimage (t_0) derived from the 3D digital model.

These labeled samples served as the input for the classifier, which iteratively analyzed pixel-level features to assign class labels across the entire image. The output of the segmentation consisted of classified raster maps that precisely delineated areas of differing conservation conditions.

These classified maps were subsequently analyzed to extract quantitative spatial metrics, including measurements of the total frescoed surface area and the extent of material loss. From these data, the percentage of decay relative to the overall decorative surface was calculated.

The pixel-based analysis, conducted to obtain a quantification within each temporal frame with a consistent estimation across each dataset, indicates a marked increase in the proportion of surface classified as loss, rising from approximately 7% of the total frescoed surface in the historical mapping ($T - 1$) to about 32% of the total frescoed surface in the current state (T_0).

These values, derived from pixel counts should be interpreted as comparative areal indicators rather than absolute metric measurements. In this framework, extending the monitoring to subsequent time steps at predefined intervals will further strengthen the diachronic assessment and represents the basis for future developments aimed at converting pixel-based estimates into metric values through calibrated orthoimages and spatially referenced datasets.

Moreover, the same supervised segmentation and classification methodology was extended to the textured polygonal mesh of the fresco, produced during the third phase of the workflow (IDM). To implement this transfer, the Random Forest classifier was trained using the previously processed high-resolution orthoimage as a reference, allowing the extraction of optimal learning parameters, including feature selection, class definitions, and threshold values, which were then applied directly to the UV-mapped texture of the 3D mesh. This approach ensured that the segmentation logic, originally developed for 2D raster data, was accurately propagated to the three-dimensional model.

The classified UV texture was subsequently projected onto the polygonal mesh within Blender, an open-source computational graphics platform, enabling the interactive visualization of the fresco's conservation state in a 3D environment (Figure 13).

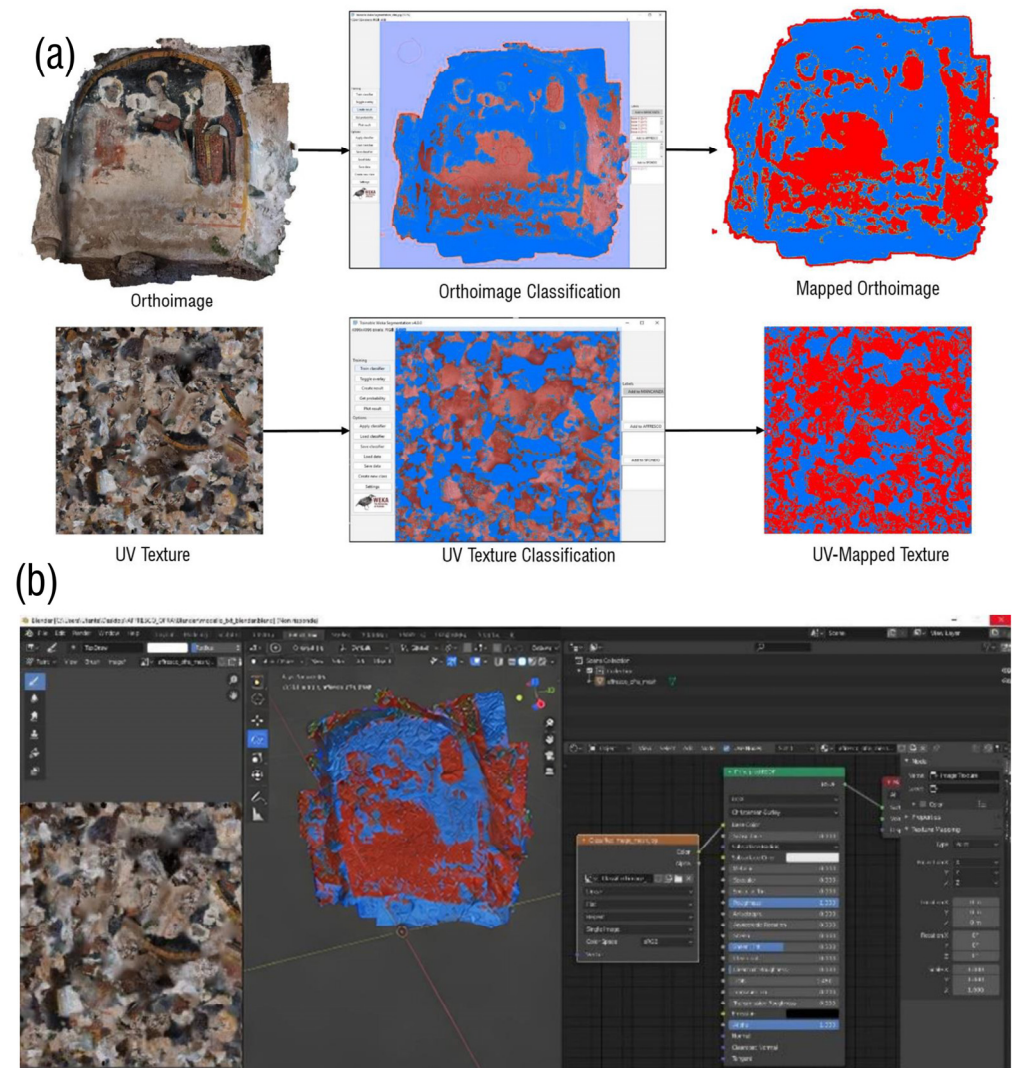


Figure 13. (a) Supervised classification workflow from high-resolution orthoimage to UV-mapped texture, (b) Projection onto the 3D polygonal mesh for interactive visualization in Blender (© Authors).

In this configuration, the mapped 3D model could be explored from multiple viewpoints, and the degradation patterns could be inspected both globally across the entire surface and locally at high resolution, preserving spatial coherence and metric accuracy. This polygonal mesh, enriched with high-resolution UV textures and conservation information derived from the supervised segmentation of the fresco surfaces, was imported into the 3DVista environment to enable interactive exploration.

The workflow allowed the integration of semantic information derived from the 2D analysis with the geometric fidelity of the 3D model, producing a digitally enriched representation suitable for both qualitative interpretation and quantitative assessment of deterioration phenomena.

To ensure reproducibility and effectiveness of the MW, the automated and semi-automated activities, including data processing pipelines and supervised classification and segmentation procedures, were subjected to a multilevel validation strategy.

In particular, each phase was verified by comparing the automatically generated outputs with reference data or expert-annotated samples, enabling the identification of discrepancies, the optimization of parameters, and the reduction in systematic errors.

Finally, to support the management and long-term monitoring of the investigated hypogeal heritage, a web-based Collaborative Platform was developed (Figure 14). The

GIS-Based System was deployed within a centralized web architecture using QGIS Server/GeoServer in combination with an Apache web server. This configuration enabled remote visualization, querying, and updating of spatial data through standard web browsers, supporting multi-user access and collaborative workflows among researchers, conservation specialists, and heritage managers. To optimize the online visualization and management of high-density three-dimensional datasets, the TLS-derived point clouds were processed using Potree Converter, which applies a hierarchical octree-based data structure to enable efficient multi-resolution streaming of large point cloud datasets. The resulting datasets were visualized using the Potree Web Viewer, enabling interactive exploration of RGB point clouds and the associated decay-mapping results directly within a browser-based interface.

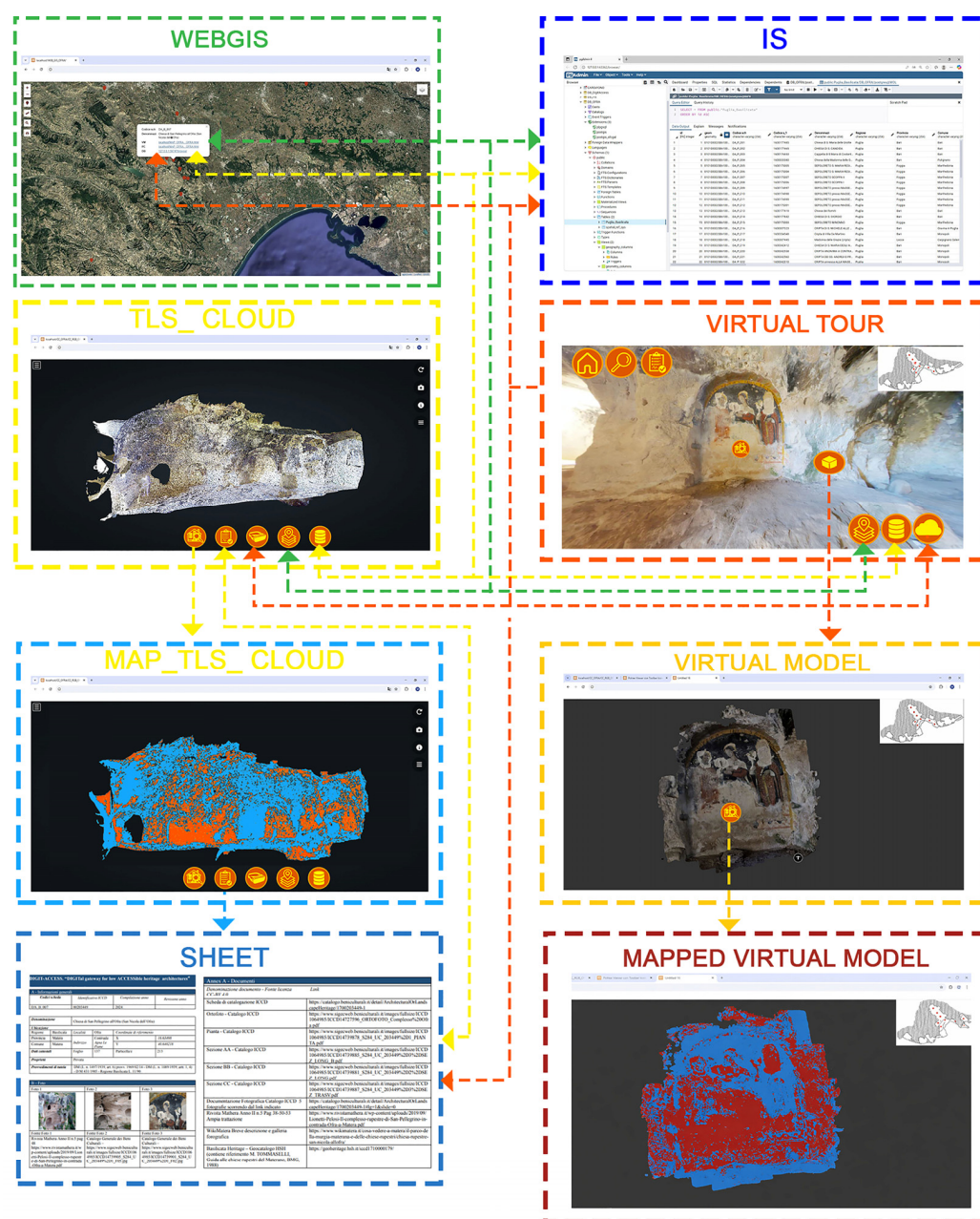


Figure 14. Integrated digital models (IDM) connected to a WebGIS platform, virtual tour/model (VT/VM), point cloud datasets, and an Informative System (IS), all integrated within a single web-based information system (© Authors).

These three-dimensional datasets were spatially and semantically integrated with the GIS layers and linked to a relational database, forming an interconnected system of digital models. This integration allows bidirectional access between geospatial data, 3D representations, and structured alphanumeric information, ensuring coherence between spatial entities and their associated diagnostic, descriptive, and analytical attributes. Within this unified information system, the processed digital models were further interconnected with additional visualization environments, including the IVE (Figure 14). Interactive hotspots were implemented to enable hierarchical navigation across different models, datasets, and levels of information. Through these access nodes, users can retrieve structured database records, diagnostic results, monitoring outputs, and related technical and archival documentation directly from spatial or three-dimensional representations.

Overall, this integrated, web-based implementation demonstrates the operational feasibility of the proposed workflow and highlights its effectiveness in supporting collaborative heritage management, multi-source data integration, and informed decision-making processes for the conservation and governance of hypogeal heritage sites.

4. Discussion

The results obtained through the application of the proposed methodological workflow highlight the effectiveness of the integrated approach in supporting the analysis, monitoring, and management of hypogeal heritage. The integration of high-resolution digital survey techniques, three-dimensional models, semi-automatic analysis procedures, and spatial information systems enabled the development of a multi-level information system capable of connecting geometric, semantic, and diagnostic data within a coherent digital environment. In particular, the combined use of TLS point clouds and photogrammetric models ensured accurate metric–geometric documentation of underground morphologies and decorated surfaces, providing the fundamental data basis for subsequent monitoring analyses and degradation mapping.

The segmentation and supervised classification procedures applied to orthophotos demonstrated the potential of machine learning techniques to support the identification and quantification of surface deterioration phenomena.

A further relevant aspect concerns the integration of the results within immersive virtual environments, digital models, and spatial information systems. The interconnection between the GIS platform, three-dimensional models, and virtual environments enabled the development of an interoperable information platform capable of facilitating data access, visualization, and exploration at different levels of detail. This configuration enhances both the dissemination and communication of results, while also supporting informed decision-making processes in the conservation and management of underground heritage. The implementation of the web-based collaborative platform further demonstrates the possibility of sharing and updating data in real time among different stakeholders involved in research, monitoring, and heritage protection activities.

Overall, the proposed approach demonstrates how the integration of digital surveying, semi-automatic analysis procedures, information systems, and virtual environments can represent an effective operational framework for the management of hypogeal sites, which are often characterized by high spatial complexity and critical conservation conditions. At the same time, the application of the MW highlights the need for a more structured integration between semantic interoperability, advanced digital modelling, and quantitative systems for the assessment of conservation conditions.

Future lines of research will focus on consolidating and extending the proposed methodological framework, with particular attention to the structured integration of semantic interoperability, advanced digital modelling, and quantitative conservation assess-

ment systems. Within this perspective, a primary area of development will concern the calibration and validation of structured conservation indicators derived from established normative frameworks, enabling their hierarchical integration within the Integrated Digital Environment. Decay phenomena may be quantified at the level of individual morpho-structural elements, aggregated at the environmental scale, and subsequently synthesized at the level of the single hypogeal unit (crypt). The reiteration of this procedure across multiple crypts may support the construction of a comparative benchmark system, enabling multi-scale assessment and decision-support processes in low-accessibility heritage contexts, building upon the structured diagnostic and digital environment methodologies previously validated in [37].

Concurrently, the research will focus on exploring the potential offered by Semantic Web paradigms, through the adoption of strategies for the progressive mapping of developed information models onto the RDF (Resource Description Framework) model and the OWL (Web Ontology Language). In this context, a central role will be played by the alignment with established reference ontologies in the cultural heritage domain, in particular the CIDOC-CRM (Conceptual Reference Model), which serves as a standard for the semantic integration of heterogeneous information related to cultural assets. Mapping to the CIDOC-CRM will enable the framing of physical entities, transformation processes, conservation events, actors, and documentation within a shared conceptual structure, thereby ensuring data compatibility with existing digital systems.

From a future-oriented perspective, the research will focus on the further formalization and validation of the concept of Digital Proximity, understood as a measurable degree of geometric correspondence, informational completeness, compensatory capacity under conditions of inaccessibility, and potential for monitoring between the physical asset and its immersive digital environment. Particular attention will be given to the identification of indicators aimed not only at measuring the geometric accuracy of the model and the semantic coherence of information, but also the capacity of the digital environment to overcome physical and cognitive barriers, support technical interpretation, and enable processes of evolutionary monitoring over time.

Within this framework, the Digital Proximity Model can be further developed as an evaluative framework, not based on the total and synchronized replication of the real object, but rather focused on assessing the ability of the digital environment to sustain knowledge, diagnostic, and decision-making processes under conditions of limited accessibility. Therefore, the evolution of the research will concentrate on the shift from measuring system “twinning” to a structured evaluation of its effectiveness in substituting, integrating, or amplifying the physical presence in processes of analysis, interpretation, and management of low-accessibility heritage.

5. Conclusions

Recent scientific contributions indicate that research on low-accessible architectural heritage is progressively moving toward more integrated digital approaches. However, a critical analysis of the literature shows that the conservation process is still frequently addressed through thematically focused contributions, in which surveying, diagnosis, monitoring, and information management are developed as partially independent domains.

Within this framework, the present research proposes a structured and integrated methodological approach that interprets knowledge production for low-accessible heritage as a dynamic, iterative, and continuity-oriented process. Inaccessibility is not treated as a residual condition to be compensated *ex post*, but as a foundational design constraint informing the entire workflow, from data acquisition to diagnostic interpretation and decision-support processes. This perspective enables the correlation of reality-based three-

dimensional models, diagnostic information, and interpretative layers within a coherent information ecosystem conceived to operate under conditions of limited, intermittent, or temporarily restricted access.

The validation of the workflow through the San Pellegrino rupestrian complex (Matera) demonstrates how the proposed approach supports remote documentation and monitoring activities oriented toward risk management. At the site scale, the multi-scale strategy implemented in the Advanced Diagnosis and Monitoring (ADM) phase enabled a comprehensive assessment of the conservation state, identifying extensive decay patterns such as biological colonization and surface deposits through range-based spatial datasets.

At the detail scale, the framework supported the diachronic monitoring of decorative apparatuses, transforming historical iconographic documentation and contemporary digital data into evidence of material loss on frescoed surfaces.

This comparative analysis allowed for the identification of critical changes and deterioration trajectories over time, providing a quantitative basis for long-term monitoring and preventive conservation decision-making, even in the absence of continuous physical access. The operational culmination of this workflow is the implementation of an Integrated Digital Environment (IDE). This web-based collaborative platform centralizes heterogeneous spatial and descriptive data, ensuring that high-density 3D datasets and diagnostic outputs are accessible to different stakeholders. By fostering a form of “digital proximity,” the IDE allows for the remote exploration of RGB point clouds and decay maps through standard web interfaces, facilitating shared interpretation and evidence-based decision-making when physical access is restricted.

From a future perspective, the research opens further developments related to the extension of the workflow to networks of low-accessible sites, integration with continuous monitoring systems, and the progressive automation of diagnostic processes, while maintaining a central role for expert judgment. In this sense, the work establishes a methodological foundation for the development of advanced digital environments for the knowledge, conservation, and management of architectural heritage characterized by high complexity and fragility.

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Abbreviations

The following abbreviations are used in this manuscript:

ADM	Advanced Diagnosis and Monitoring
CDS	Comprehensive Digital Survey
CS	Conservative State
GIS	Geographic Information System
IDE	Integrated Digital Environment
IDMs/IDM	Integrated Digital Models
IS	Informative System
IVE	Integrated Virtual Environments
Map_Ortho	Mapped Orthophoto
Map_RGB_Mesh	Mapped
Map_TLS_cloud	Mapped Terrestrial laser scanning point cloud datasets
MDS	Multidisciplinary Data Structuring
MW	Methodological Workflow
PK	Preliminary Knowledge
RGB_Mesh	Textured mesh models generated from photogrammetric data
S_TK	Structuring of Technical Knowledge
Shp_image	Spherical image
SP	Survey Plan
TLS	Terrestrial laser scanning
TLS_Cloud	Terrestrial laser scanning point cloud datasets
UAVs	Unmanned Aerial Vehicles
VMs/VM	Virtual Models
VTs	Virtual Tours

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