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Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks

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Chapter 1
Introduction

Gianmarco De Felice, Fabiana Di Ciaccio, Speranza Falciano, Lidia Fiorini, Rodorico Giorgi, Cristiano Riminesi, and Grazia Tucci

Abstract Cultural Heritage, as a bridge between the past and future, represents the identity, values, and collective memory of societies. This volume, Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropogenic Risks, presents the Spoke 7 results within the CHANGES project, a pioneering initiative funded by the European Union's NextGenerationEU framework through the National Recovery and Resilience Plan (NRRP). The book explores innovative, interdisciplinary approaches to safeguarding Cultural Heritage in the face of climate change, natural disasters, and

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anthropogenic threats, integrating expertise from engineering, material sciences, digital technology, and humanities to address the complexities of protecting both tangible and intangible cultural assets. The thematic sections of this book emphasize cutting-edge solutions, including digital twins, advanced monitoring systems, eco-sustainable materials, and preventive conservation methodologies. Moreover, case studies highlight real-world applications, spanning historic cities, landscapes, monuments, and individual artifacts. This collection underscores the importance of preparedness, resilience, and sustainability in Cultural Heritage preservation, advocating for collaboration across disciplines and scales.

Keywords Cultural Heritage · Climate change · Natural and anthropogenic risks · Interdisciplinary approach · Innovation · CHANGES project · NRRP—Next GenerationEU

1.1 The Spoke 7 Research Group: The Context and Its Mission

Cultural Heritage, in its most recent and internationally recognized definition, is described as "a group of resources inherited from the past which people identify, independently of ownership, as a reflection and expression of their constantly evolving values, beliefs, knowledge and traditions. It includes all aspects of the environment resulting from the interaction between people and places through time" (Consiglio d'Europa, 2005).

Cultural Heritage has always been exposed to both natural and man-made risks, but only in recent years it has become the focus of studies and projects aimed at developing shared strategies for risk management and reduction. As a result, new approaches and methods for safeguarding and conserving assets have been, and are still being, designed and enhanced (Commissione Europea, 2019). This book, Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks, presents the intermediate results of the Spoke 7 research group within the "Cultural Heritage Active Innovation for Sustainable Society"—CHANGES project (Fondazione Changes, 2023), funded by the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3 funded by the European Union—NextGenerationEU (Agenzia per la Coesione Territoriale, 2023).

CHANGES is an extensive partnership funded under the Theme 5, "Humanistic Culture and Cultural Heritage as Laboratories of Innovation and Creativity." It aims to establish an international hub for training, research, and technological transfer in the fields of Culture and Cultural Heritage. The goal is to enhance the value of Italy's Cultural Heritage by promoting new sustainable approaches to its protection

and enjoyment, creating stable partnerships between research and industry, and offering employment opportunities in the sector.

The project partners contribute to the six missions of the NRRP (i.e., Digitalization, innovation, competitiveness, and culture; Green revolution and ecological transition; Infrastructure for sustainable mobility; Education and research; Cohesion and inclusion; Health) by re-modeling CH as a foundational research domain and a key driver of innovation and competitiveness, able to advance education and strengthen social cohesion. The content of the WPs is fully aligned with the 'do no significant harm' (DNSH) principle guiding national and EU environmental regulations (Italia Domani, 2021).

The organizational structure of the CHANGES project draws inspiration from the concept of the "bicycle wheel," known in English as the "hub and spoke" model, where the "hub" is the central part of the wheel, and the "spokes" are the connecting rods. In this framework, the CHANGES Foundation acts as the hub, the central driving force of the project, while the thematic spokes represent the wheel's connecting components. Each of the nine spokes plays a fundamental role in the project and collectively forms complementary areas of expertise to build an extensive interdisciplinary ecosystem spanning the humanistic, technological, and cultural fields.

These spokes aim to support the protection, enhancement, and sustainable transformation of both tangible and intangible Cultural Heritage, addressing challenges such as digital conservation, the creation of creative ecosystems, the promotion of sustainable tourism, and the management of natural and anthropogenic risks affecting cultural assets.

The University of Florence coordinates the Spoke 7 in collaboration with the Gran Sasso Science Institute; the other partners include the Universities of Bologna, Naples (Federico II), Roma La Sapienza and Roma Tre, the National Research Council (CNR), the Opificio delle Pietre Dure (OPD), the Lazio Technological District for Cultural Heritage (DTC Lazio), the Italian Institute for Conservation and Restoration (ICR) and the Politecnico of Torino as associate partner.

Spoke 7 intends CH as an extensive and inclusive domain. The overall aim of the Spoke 7 is to advance the tools for protection and conservation of CH focusing on incumbent challenges caused by climate change and natural and anthropic risks (Aktürk & Hauser, 2024). The traditional distinction between natural and man-made hazards is in fact challenged by the combination and interaction of different hazards and causes, as natural disasters also cause migration and social conflicts, and human behavior accelerates natural processes (Blaikie et al., 2014). Phenomena related to climate change and natural/anthropic risks raise new research questions and open new challenges for modern societies, requiring a broad multidisciplinary approach towards problem solving, emphasizing the importance of preparedness and resilience (Genovese, 2021). A multi-scale approach is applied to encompass various scenarios and address both general and specific issues. Relevant case studies are identified in the following areas: environmental and historical landscapes, historic cities and minor historic centers, built heritage and monuments, and works of art.

The Spoke works to identify and strengthen the interrelations with the pillars of sustainability by designing and testing new heritage-based safety and energy

efficiency systems, supporting digital and green transitions for enhancing the preparedness of cultural managers and local communities to natural and anthropic threats. In this context, efforts are being made towards an in-depth assessment of the tools for carbon leakage measures in CH, low energy consumption devices for monitoring, self-curing conservation products, digitization tools for preventive conservation of sites and collections, and integrated data management systems.

The development of diverse materials and products through circular mechanisms and low-carbon emission processes is considered a valuable indicator of innovation. Preventive conservation strategies and monitoring processes will help reduce the technological gap by testing more effective and efficient planned-maintenance tools (e.g. early hazard detection systems). To contribute to upgrade the accessibility standards, hazards repositories will be interoperable and compliant with FAIR principles (Wilkinson et al., 2016). Spoke 7 will set the foundations for a strong, energy-aware, multidisciplinary community within the broader heritage community.

The importance of this volume lies not only in the cutting-edge solutions it explores, but also in its function as a dynamic assessment of an evolving project. By sharing these results, the authors invite the wider research and practitioner community to engage with, and build upon, the methods and insights presented. This openness to collaboration and continuous improvement is essential for addressing the increasingly complex challenges that Cultural Heritage conservation now faces.

The book's content reflects the multidisciplinary nature of the project, integrating knowledge from fields such as engineering, climate science, digital technology, and material sciences. The diverse case studies, ranging from the digital documentation of architectural sites to the sustainable restoration of historic buildings, illustrate how these methodologies can be applied to real-world scenarios. In particular, the focus on Italian cities (e.g., L'Aquila, Bologna, Firenze, etc.) demonstrates the local relevance of the research while also offering solutions with global resonance. As climate change continues to disrupt environments worldwide, the strategies developed here provide a valuable model for other nations facing similar threats to their cultural assets.

Moreover, this volume underscores the necessity of a comprehensive, multi-hazard approach. By integrating the latest advancements in digital twins, monitoring technologies, sustainable materials, and risk assessment protocols, the book outlines a clear path for how the Cultural Heritage sector can adapt to an increasingly uncertain future. At this critical halfway point, the research team has laid a solid foundation, yet the ongoing nature of the project ensures that these strategies will continue to be refined, tested, and further developed in the coming years.

Yet, the journey is far from over. The lessons learned at this stage will inform the next phases of the project, driving forward more resilient, sustainable, and forward-thinking conservation and protection approaches.

We extend our sincere appreciation to the authors and contributors for their dedication and forward-looking approach. By sharing their intermediate findings at this stage, they not only enrich the global discourse on Cultural Heritage, but also foster an environment of ongoing innovation and collaboration.

It is our hope that this book will inspire continued research, dialogue, and action, as we collectively work to safeguard the Cultural Heritage that defines and unites us all.

1.2 Structure of the Book

This volume is organized into five main parts, each addressing a specific thematic area within the CHANGES project. Each part comprises several chapters that examine different dimensions of Cultural Heritage preservation, offering multidisciplinary insights and practical approaches. Summary of the themes explored in each part and an overview of the chapters are presented below.

1.2.1 Part I: Tangible Heritage Knowledge and Cultural Context

This part of the Volume summarizes the work of three Universities that, with a common thread and complementary skills, try to address the issue of knowledge of tangible heritage and its cultural context, from a risk management perspective. The in-depth knowledge of the risk, gained through case studies, is an opportunity to identify strategies for its mitigation: know the risk to govern it, or at least to try—as much as possible—to mitigate it.

From the classificatory and methodical study of Sapienza, full of national and international regulatory references, indicators and data, knowledge and categories of risk, we pass through a broad spectrum of possible methodologies—proposed by the GSSI—to be applied to the study of risks and the consequent need for prevention, declined from time to time on a well-defined territory (whether national or urban), until we enter the dimension of the historic city. Concerning the historic city of L'Aquila the Network model between academic research, specialists, public administrations and communities fits perfectly. Finally, the case study of the historic city of Bologna analyses a melting pot of risks and opportunities of the contemporary city, but also a "counter-model of contemporary urban development", suspended between natural risks and conservation, between history, memory and urban transformations, aesthetic values of the past, new citizenships and new forms of living, planning and entropy, public space and private space.

It is well understood that risk analysis does not stop only at indicators and quantitative analyses but must necessarily associate with the latter factors such as the well-being of communities, their relationship with Cultural Heritage, new forms of civilization and of inhabiting, perhaps even re-semanticizing, the places that bear Cultural Heritage.

Reading these pages, it is clear that an exquisitely humanistic approach does not prevent, indeed happily meets the most advanced frontiers of new technologies, IT tools (with advanced and complex platforms) and Artificial Intelligence, leading to a hybridization of knowledge that ends up generating and proposing composite models (IT, instrumental, intellectual, governmental) of risk management or support for decision-making processes.

This global approach aims not only to create specialized knowledge, but also to support political decision-makers, cultural operators and public administrations with adequate tools. The aim is to respond in effective and innovative ways to the new challenges of contemporaneity, where the effects of climate change are added, as a further variable, to the multi-risk equation of—already present—natural and anthropic risks on the territories. A proactive strategy to risk analysis is therefore proposed, promoting and encouraging greater resilience of territories, with an operational view applied to the different scales analyzed; without forgetting that historical sciences can place themselves at the service of communities and decision-making processes which can, more or less, have repercussions on communities themselves and their Cultural Heritage.

Chapter 2 establishes a methodological framework for analyzing multi-source data to assess and preserve outdoor tangible heritage. It consolidates hazard classifications, indicators, and protocols into a unified risk assessment framework, addressing gaps in current quantitative methods. Chapter 3 explores the case studies from the Spoke 7 project, emphasizing risk analysis, urban planning tools, and community-driven approaches for Cultural Heritage management, with a focus on the city of L'Aquila.

Chapter 4 highlights the historical city as a model for urban resilience and aesthetics, integrating nature-based solutions and urban heat island analysis through the Bologna case study.

1.2.2 Part II: Digital Twins and Documentation for Cultural Heritage

The contributions presented in this Part converge around a critical yet often overlooked aspect of Cultural Heritage preservation: the comprehensive documentation of the processes through which digital data are acquired and processed, forming the foundation on which preservation projects are built. This section proposes a preliminary protocol that aims to balance standardization with adaptability, offering an initial framework for addressing the multifaceted challenges faced by Cultural Heritage professionals. It emphasizes a holistic methodology that bridges traditional techniques with cutting-edge technologies, such as 3D digitization, photogrammetry, and Virtual/Augmented Reality (VR/AR), to support the creation of detailed and dynamic records of cultural assets. As Cultural Heritage sites confront threats ranging from natural disasters to urban encroachment, this

section underscores the necessity of a robust, interdisciplinary approach that integrates technological, historical, and material science perspectives.

At the heart of this discourse lies the notion of the Digital Twin, a concept that moves beyond static documentation to offer a dynamic, real-time representation of heritage assets. These digital models serve not only as repositories of accurate data but also as tools for predictive analysis and informed decision-making. They facilitate risk-mitigation strategies that are both proactive and sustainable, ensuring that preservation efforts remain economically viable and ecologically sensitive.

By interweaving case studies with theoretical frameworks, the section also underscores the importance of metadata and paradata in contextualizing documentation processes. It emphasizes transparency and replicability, advocating for documentation protocols that record not only the data but also the narrative behind their creation. This approach aligns with broader European initiatives on Cultural Heritage digitalization, promoting cross-border collaboration and knowledge sharing.

In summary, this section positions thorough and comprehensive documentation as a fundamental responsability within heritage conservation, framing it as a dynamic and integrative practice essential to preserving the cultural and historical identity of the built environment.

Chapter 5 introduces a protocol for standardized documentation, aligning with European digitization strategies and focusing on sustainable methodologies. Chapter 6 discusses the integration of informative models with digital twins, addressing challenges in transferring data between structural analysis tools.

Several case studies are then presented and analyzed. Chapter 7 presents the Giovanni Pisano's pulpit, documented through scanning and photogrammetry systems and monitored with mechanical tests to assess the static behavior of the structure. Chapter 8 focuses on the Sanctuary of Vicoforte, where advanced monitoring systems and satellite data are used to create a digital twin for real-time diagnostics. In Chap. 9 the Ponari Nymphaeum is presented, highlighting its structural analysis and 3D virtual documentation in support to conservation. Chapter 10 evaluates the monitoring of artworks in Viterbo's Colle del Duomo Museum, combining microclimate sensors with UV-based 3D diagnostics techniques. Finally, Chap. 11. analyzes the Grotta degli Animali at Villa di Castello from a digital documentation perspective, emphasizing the importance of three-dimensional digital models for understanding artefacts and designing environmental monitoring systems.

1.2.3 Part III: Monitoring, Assessment and Preventive Conservation of Heritage Against Climate Change and Anthropic Risks

The preservation of outdoor heritage is increasingly challenged by various risks, including environmental factors, human activities, and climate change. Effective monitoring, risk assessment, and management strategies are essential for the preventive conservation of Cultural Heritage assets. This overview discusses recent developments in these areas, aiming at proactively addresses potential threats to heritage assets, ensuring their longevity and accessibility for future generations.

This Part focuses on new applications for monitoring impacts due to multi-hazard, natural and anthropic, and mitigating climate damage. Relevant case studies at different scales were considered to formulate multiscale procedures based on improved modeling approaches, in order to introduce the effects of environmental and mechanical damage and the development of digital sensing and monitoring technologies integrated with methods for seismic risk assessment. The integration of digital detection and monitoring technologies with multi-hazard risk methods is also proposed, and application protocols are also described. In the specific, Chap. 12 presents macromechanical models to analyze damage mechanisms in masonry structures due to mechanical and environmental actions. Chapter 13 proposes a framework for the dynamic conservation of wine cultural landscapes, integrating geospatial data to adapt to climate changes. In Chap. 14 strategies for preventive conservation in semi-confined environments are explored, with a focus on microclimatic changes in the Grotta degli Animali. Chapter 15 investigates vandalism as a threat to Cultural Heritage, offering historical analyses and prevention strategies; finally Chap. 16 studies the effects of climate change on maritime heritage, using the Island of Motya as a case study to propose integrated management strategies.

1.2.4 Part IV: Restoration and Sustainable Strategies for Heritage Preservation Against Risks and Climate Change

The preservation of Cultural Heritage against natural/anthropic risks and the effects of climate change raises new research questions and new challenges for modern societies, requiring a broad multidisciplinary approach that encompasses different scenarios and controls different scales, from landscape to built heritage and artefacts.

The community is required to find the right balance between the necessity of intervening to protect cultural assets from risks and the imperative to limit interventions to what is strictly necessary. A restoration strategy cannot be separated risk assessment and its impact on the cultural asset.

It is not possible to summarize the variety and complexity of this topic in a few contributions: in one case it is a matter of protecting the artwork in emergency conditions, in another case it is a matter of developing technologies to prevent the loss of the asset after a natural disaster or restoring the heritage to protect the landscape from natural hazards.

All these scenarios have a minimum common denominator: the use of advanced technologies to achieve an accurate assessment of the risk and the necessity to intervene, and the development of innovative solutions to minimise the impact of mitigation works on the cultural asset.

The glue between the different scales is represented by the development of sustainable intervention protocols and strategies that can be applied in different scenarios from the ordinary ones related to maintenance and preservation of the asset, to the emergency contexts aimed at avoiding its loss.

A further distinguishing character is represented by the strong multi- and interdisciplinary nature that allows the development of restoration strategies where innovative materials and technologies coexist, together with the recovery of ancient knowledge and techniques, as distinctive signs of a culture to be preserved.

This Part collects three contributions related to different emerging scenarios, either caused by natural hazard or climate change. Chapter 17 brings together transdisciplinary expertise focusing on terraced landscapes and their multidimensional values. Shared methodologies of risk assessment and mitigation strategies are outlined to mitigate hydrogeological risks while preserving cultural practices. Chapter 18 is devoted to the development of new technologies to ensure the safety of historic buildings against seismic risk while preserving not only their appearance with fair face stone masonry, but also their original construction rules. Chapter 19 illustrates the potential of using volatile binders in emergency contexts to secure works of art by means of temporary consolidation that allows transport in view of the subsequent restoration work, ensuring adequate consolidation and reversibility. The variety of the three contributions, the disciplinary experiences involved, and the different scales of intervention give rise to the complexity of developing shared methodologies and strategies for restoration and sustainable management of Cultural Heritage.

1.2.5 Part V: Green Materials and Methodologies for Conservation

The research and development of new materials and methodologies for the conservation of Cultural Heritage is a process that never ends, since the challenges we face are always new due to the great variety of new materials used in contemporary art for the creation of artistic works, for the environmental conditions of conservation which are changing significantly due to the continuous growth of urban areas with evident repercussions in terms of air pollution and the climate emergency, which is designing new and often dramatic scenarios.

At the same time, the great development of modern technologies and increasingly in-depth knowledge in the domain of nanoscience and biotech offers increasingly high-performance and long-lasting solutions.

In this project, complex conservation challenges are addressed from the perspective and the ever-growing need to adopt eco-sustainable materials and solutions, in compliance with the guidelines outlined by the Green Deal and the 2030 EU agenda. Technologically innovative approaches to systematization in a circuit of sustainable and environmentally friendly enhancement and fruition is an urgent need for the global community.

The contributions of this part embrace very different issues, moving from archaeological assets in outdoor environments, to contemporary mural paintings for which the term Street-Art is now universally recognized. The research here presented is united by the need to obtain materials from renewable sources through eco-sustainable processes, alternative to petrochemical-derived chemicals, thus representing some of the ambitious objectives of the project, of which the most significant results are reported in this part.

Chapter 20 investigates the use of dry-cleaning techniques that do not involve the use of solvents, for sensitive cultural artifacts, ensuring minimal damage during the cleaning process. Chapter 21 addresses biodeterioration in stone monuments, proposing eco-friendly biocides and integrated conservation strategies; in Chap. 22 the formulation of gels and composites from the extraction of 'green'-classified oligomers and polymers from renewable sources is presented, while Chap. 23 explores formulations for the consolidation and protection of surfaces using composite systems of natural origin as novel green polymers, gels, and composites. Similarly, Chap. 24 focuses on nanocellulose compounds for reinforcing organic supports in cultural artifacts, promoting environmentally friendly consolidation methods and Chap. 25 deals with sustainable coatings for preserving street art, combining durability with aesthetic compatibility. Finally, Chap. 26 examines the use of materials obtained via 3D printing for the reintegration of missing structural and decorative restorations, emphasizing reversibility and lightweight materials.

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References

Agenzia per la Coesione Territoriale. (2023). *Next Generation EU e il Piano Nazionale di Ripresa e Resilienza*. Accessed on November 2024, from https://www.agenziacoesione.gov.it/dossier_tematici/nextgenerationeu-e-pnrr/

Aktürk, G., & Hauser, S. J. (2024). Integrated understanding of climate change and disaster risk for building resilience of cultural heritage sites. *Natural Hazards*, 1–26.

Blaikie, P., Cannon, T., Davis, I., & Wisner, B. (2014). *At risk: Natural hazards, people's vulnerability and disasters*. Routledge.

Commissione Europea. (2019). *Direzione generale dell'Istruzione, della gioventù, dello sport e della cultura, Quadro d'azione europeo sul patrimonio culturale*. Ufficio delle pubblicazioni. https://data.europa.eu/doi/10.2766/622226

Consiglio d'Europa. (2005). *Convenzione quadro del Consiglio d'Europa sul valore dell'eredità culturale per la società*. Consiglio d'Europa, Faro (Portogallo), 27, 2005.

Fondazione Changes. (2023). *Cultural heritage active innovation for next gen sustainable society*. Accessed on November 2024, from https://www.fondazionechanges.org/

Genovese, R. A. (2021). Cultural heritage, climate change, intercultural dialogue and strategies for integrated conservation. In *New metropolitan perspectives: Knowledge dynamics and innovation-driven policies towards urban and regional transition* (Vol. 2, pp. 1939–1951). Springer International Publishing.

Italia Domani. (2021). *The DNSH principle (Do No Significant Harm) in the NRRP*. Accessed on November 2024, from https://www.italiadomani.gov.it/en/Interventi/dnsh

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., & Mons, B. (2016). The FAIR guiding principles for scientific data management and stewardship. *Scientific Data, 3*(1), 1–9.

Part II
Digital Twins and Documentation for Cultural Heritage

Chapter 9
The Ponari Nymphaeum of Cassino: First Steps Towards a New Approach

Eugenio Polito, Arturo Gallozzi, Vincenzo Graffeo, Francesca Pierdominici, and Alessandra Ferrara

Abstract The Ponari Nymphaeum, dating from the first century BC to second century AD, is an important example of Roman residential architecture located in the ancient Roman town of Casinum, at the foothill of Montecassino Abbey. It has a rectangular structure with nine square niches, and was originally decorated with rustic mosaics evoking caves and caverns. Later, the walls were covered with painted plaster imitating marble, consistent with the evolution of Roman taste. The nymphaeum opens onto an atrium with an impluvium, paved with a white mosaic and decorated with paintings simulating a garden (paradeisos) and an isodomic wall structure. The presence of the atrium makes the Ponari nymphaeum unique, distinguishing it from the more common type of nymphaeum as an independent structure. Besides illustrating the different construction and decorative phases of the nymphaeum, the paper describes the survey and documentation techniques used, including laser scanning and photogrammetry, to create 3D digital models and a 2.5D virtual tour. Furthermore, it highlights the critical issues related to the nymphaeum structure and the need for conservation interventions. It emphasises the importance of an in-depth analysis of structural materials and the definition and cataloguing of critical processes and risks, both natural and man-made, that threaten the integrity of the archaeological asset. Finally, it proposes the implementation of multi-criteria

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monitoring procedures to continuously assess the state of conservation of the Ponari Nymphaeum, thus ensuring its long-term preservation.

Keywords Ponari Nymphaeum · Rustic mosaic · Heritage Building Information Modelling (HBIM) · Digital twin · Structural Health Monitoring (SHM) · Cassino

9.1 The Ponari Nymphaeum of Casinum: Architecture, Decoration and Restoration of a Roman Monumental Complex

The Ponari Nymphaeum (Fig. 9.1) is located upstream of the urban system of ancient Casinum, a short distance from the Theatre, occupying one of the northern quadrants where the main domus of the Roman city were located (Fig. 9.2) (Carettoni, 1940; Polito, 2013; Tanzilli, 2016).

The monument dates from between the first century BC and the second century AD. It is a rectangular room, partially recessed into the slope, closed on three sides and completely open on the front, and covered by a cement barrel vault. The three straight walls are enlivened by the presence of nine square niches with a flat roof. The floor of the Nymphaeum is decorated with a refined polychrome mosaic floor, forming a chessboard in which fragments of coloured marble are inserted. The weaving, despite the numerous inserts, is quite regular and accurate, even if the

Fig. 9.1 3D point cloud processing with textures

Fig. 9.2 Location of the Ponari Nymphaeum in the context of the archaeological area of the Roman Casinum

Fig. 9.3 Left: polychrome mosaic floor in the Nymphaeum—right: black dotted white mosaic floor and marble inserts in the entrance area

colours of the tesserae are randomly distributed, with only the alternation between the white and coloured ones being strictly respected (Fig. 9.3). The use of coloured marbles, the horizontal warp and the chequered pattern seem to point to comparisons attested in the late Republican period (Valenti, 1992).

The walls, on the other hand, preserve the remains of two different decorations: the first is called rustic mosaic, which, in a second phase, is covered with painted plaster imitating marble (Valenti, 1992, 1994). The rustic decoration, made with the intention of artificially evoking caves and underground caverns connected with water (Neuerburg, 1965), is executed with the application on the wall of shells, coloured glass in geometric shapes, limestone fragments, Egyptian blue and white quartz tiles (Fig. 9.4 left). It has been possible to identify a tripartite decorative scheme: in the upper part it is organised in parallel bands, in the middle part it is marked by the presence of niches surmounted by triangular pediments, and in the lower part, which develops below the floor of the niches, it is delimited at the top by a band with alternated circular and rhomboidal polychrome glass tiles, characterised by a lozenge grid pattern that recalls cocciopesto and wrought stone floors of the late Republican period (Valenti, 1994).

Fig. 9.4 Left: detail of the rustic mosaic warp—right: right wall of the Nymphaeum, painted plaster imitating marble slabs

The Ponari Nymphaeum probably underwent a series of renovations that also affected the rustic mosaic wall decoration, which was replaced with painted plaster. This change reflects the evolution of taste and decorative techniques in the Roman period: as time went by, painted plaster established itself as the main technique for interior decoration, thanks to its versatility and the possibility of creating increasingly refined pictorial effects (Falzone, 2007). In the case of the Ponari Nymphaeum, painted plaster is characterised by imitations of coloured marble slabs. This decorative style, typical of the first century AD, was characterised by the elegance and refinement of its compositions (Fig. 9.4 right).

The extension of the excavation towards the area in front of the nymphaeum revealed that the room opened onto an atrium with an impluvium (rainwater collection basin), bordered by side walls marked vertically on the façade by pilasters (Betori, et al., 2009; Betori, 2009). The area is paved with a white mosaic and is arranged around a square compluvium basin lined with white marble. The painted decoration of the walls of the atrium is marked by two registers: at the bottom runs a paradeisos-themed baseboard in a deep red colour, on which beasts are depicted against a background of shrubs, intended to simulate a garden scene (Fig. 9.5 left) (Guiral & Mostalac, 2005). Above this runs an imitation in painting of an isodomic wall apparatus. On the right head of the nymphaeum half of a standing figure apparently moving towards the entrance of the nymphaeum is preserved (Fig. 9.5 right). Due to the considerable stylistic difference from the feline figures on the plinth, it is probably a later insertion testifying to a further decorative phase of the com-plex. The presence of the atrium in front of the nymphaeum and the adjacent masonry structures suggests a more complex organism, hypothesising a large domus inserted into the fabric of the late republican city (Betori et al., 2009; Betori & Vincenti, 2017).

Fig. 9.5 On the left detail of the plinth of the atrium—on the right detail of the standing figure incident on the right head of the Nymphaeum

9.2 Specific Achievable Objectives

OO1: Evolution of the state of the art and semantic organisation
The evolution of the state of the art and semantic organisation in the Ponari Nymphaeum is evident in the different decorative phases that affected the structure (Valenti, 1992, 1994). Initially, the Nymphaeum had a rustic mosaic decoration, using simple materials such as shells, coloured glass and fragments of limestone. This decorative choice, typical of an older taste, aimed to evoke the natural environment of caves and underground caverns, in line with the Nymphaeum's function as a place dedicated to water (Neuerburg, 1965; Cifarelli, 1995; Cifarelli & Valenti, 1999). Later, the Nymphaeum underwent a significant transformation, with the abandonment of rustic mosaic and the introduction of painted plaster. This new decorative technique, typical of the first century AD, reflected the evolution of taste towards greater refinement and elegance. The imitation of coloured marble slabs in the plaster testifies to the search for greater preciousness and a more sophisticated aesthetic. The semantic organisation of spaces also underwent an evolution. Initially, the Nymphaeum appeared as a rectangular room with nine niches, entirely dedicated to rest and pleasure of the senses.

The extension of the excavation then revealed the presence of an atrium in front of it, also decorated on the walls, in a first phase, by rustic mosaic, later covered by paintings simulating a garden (*paradeisos*-themed), the floor instead presenting a white mosaic and an *impluvium* (Betori, 2009; Betori et al., 2009). The presence of the atrium suggests a very precise organisation of spaces, which served as a reception area and passage to the Nymphaeum. The choice of representing a *paradeisos*-themed in the atrium, with its connotations of abundance

and serenity, contributed to creating a pleasant and relaxing atmosphere, typical of a place dedicated to conviviality and pleasure.

OO2: Analysis of available experimental data
OO3: Definition of a Digital Twin
OO4: Definition of a Web GIS model
OO5: Preparation of a monitoring system.

The objectives of the documentation campaign are:

Table 9.1 Master data

Object	Nymphaeum
Scale of reference	The Ponari Nymphaeum in the archaeological area of *Casinum*
Original/current use	Nymphaeum Probable annexe of a Roman domus
Author	–
Location	Archaeological site of Casinum, via Montecassino SR 149, Cassino (FR)
Geographic coordinates	41.484450097717385 N—13.822469593767584 E
Chronology	First century BC—First century AD
Property	Università degli Studi di Cassino e del Lazio Meridionale (formerly owned by the Ponari family)
ICCD file	–
Conservation authority	Soprintendenza Archeologia, belle arti e paesaggio per la provincia di Frosinone e Latina
Constraints	Archaeological constraint: "Ninfeo Ponari, strutture murarie" (Ex Lege 1089/39:D.M. 05.10.1974)—Identificativi Regione Lazio: ID RL arp_0202—Beni del patrimonio archeologico—puntuale—art.10 *d.lgs.* 42/04 (Fig. 9.6 left) At the edge of the Montecassino Natural Monument, established by Presidential Decree Lazio 11 March 2010, n. 154 (B.U.R. of 14 April 2010, n. 14), significant naturalistic and historical-archaeological interest - Management Body: Ente Parco Monti Aurunci
Keywords	Cultural Heritage; Ponari Nynphaeum of Cassino; Heritage Building Information Modelling (HBIM); Structural Health Monitoring (SHM); Finite Element Modelling; Structural Analyses; Web Gis comunication
Risk Map (MiC) Directorate General for Cultural Heritage Security	Cultural Heritage: not signalled Vulnerability/risk: not signalled Hydrogeological risk—ISPRA: Landslide risk, potentially high risk area (Fig. 9.6 right)
Type of risk	Anthropogenic risk: discontinuous maintenance Natural/environmental risks: marked steepness of the site with risk of landslides, risk of damage from wild animals (wild boar) Effects of climate change: increased atmospheric precipitation Indirect risks: seismic vulnerability of the Cassino area

(continued)

Table 9.1 (continued)

Research team	CdE DTC Lazio (Distretto Tecnologico beni e attività Culturali—Centro di Eccellenza) Scientific Advisors: prof. Eugenio Polito; prof. Arturo Gallozzi UNICAS (Università degli Studi di Cassino e del Lazio Meridionale): – Dipartimento di Scienze Umane, Sociali e della Salute – DART Laboratorio di Documentazione, Analisi, Rilievo e Tecnica dell'Architettura, responsabile: prof. Michela Cigola – LaRSArA Laboratorio di Ricerche Storiche e Archeologiche dell'Antichità, responsabile: prof. Eugenio Polito Researchers CdE DTC Lazio: dr. Vincenzo Graffeo (Senior); dr. Francesca Pierdominici (Junior); dr. Alessandra Ferrara (Junior) Collaboration: – LAPS—UNICAS—Laboratorio di Analisi e Progettazione Strutturale: prof. Maura Imbimbo (Responsabile); prof. Valentina Tomei; prof. Ernesto Grande; dr. Marina Serpe – LaGGS—UNICAS—Laboratorio di Geotecnica, Geologia e Strade, responsabile: prof. Giuseppe Modoni – ENEA—Centro Ricerca Frascati: dr. Michele Arturo Caponero; dr. Cristina Mazzotta; dr. Davide Vicca; dr. Rosaria D'Amato – CRITEVAT—UNIROMA Sapienza—Centro Reatino di ricerca di Ingegneria per la Tutela e Valorizzazione dell'Ambiente e del Territorio: prof. Leonardo Paris; prof. Maria Laura Rossi

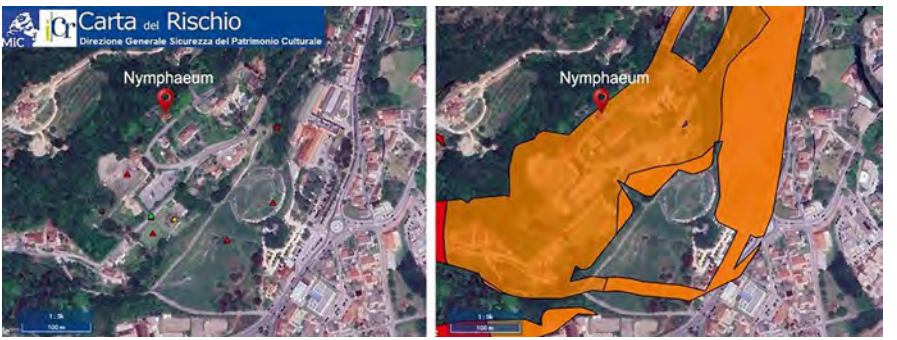

Fig. 9.6 Risk Map: General Directorate for the Safety of Cultural Heritage—Ministry of Culture. On the left a map of the Cultural Assets reported in the archaeological area of Casinum—on the right ISPRA Hydrogeological Risk map, Landslide Risk

- production of a metric representation of the shape and appearance of the artefact, (to carry out mapping of the state of preservation and crack paintings).
- production of a three-dimensional model to assess environmental and anthropic risks.
- realisation of a three-dimensional model for the representation of the crack framework.
- realisation of a three-dimensional model for communication.
- support the monitoring system for structural diagnostics (Table 9.1).

9.3 Survey, Monitoring and Diagnostic Techniques

Considering the research objectives, it was decided to produce different types of digital models aimed at investigating specific aspects (Gallozzi et al., 2017). Surveys were carried out to analyse the site's environmental conditions: terrain acclivity and level of accessibility, exposure and any interference from conterminous vegetation: the Ponari Nymphaeum site is composed of archaeological remains ranging from masonry works to floor and wall decorations, so it is important to use the best data acquisition and processing strategies, depending on the individual archaeological specificities.

For the survey campaign, the combined use of laser scanning and photogrammetry was chosen (Gallozzi et al., 2017; Caponero, 2021). Laser scanning allows the production of a digital model with good definition that can be used for the cognitive purposes of dimensional and material aspects. Photogrammetry makes it possible to obtain a restitution with a higher resolution and more detailed textures. On the Ponari nymphaeum, the laser scanner survey is integrated with spherical panoramas realised with an external camera on a panoramic head. In this way, thanks to the use of the High Dynamic Range (HDR) technique, the image from the 3D scanner's internal camera is replaced with a higher resolution image with better exposure compensation.

In the next post-processing step, the point cloud is processed (Figs. 9.7 and 9.8). The quality of the surface model depends on both the quality of the point cloud and the algorithm used to generate the mesh surface from the point sets (in this case the Poisson algorithm is used). From the textured 3D model, 2D graphics are extracted: horizontal and vertical sections containing the specific information. The 3D model obtained in this way can be used for the monitoring of the asset over time, for the evaluation of the crack framework and for the purposes of dissemination for the creation of virtual tours.

A second output is the creation of a 2.5D model: a virtual tour of the nymphaeum realised with spherical panorama photos and hotspots to navigate the environment and access information content. Two types of hotspots can be created: (1) Dynamic: moving model; (2) Static: photos and cards (Fig. 9.9).

Finally, the georeferenced 3D model placed on the web GIS at the spatial scale, accompanied by the database and links to retrieve the information collected can be published and shared on the web (Fig. 9.10) (Pierdominici, 2020).

Workflow

- inspections and instrument testing
- acquisition planning
- laser scanner acquisitions
- measurement of photogrammetric targets placed on the artefact and photographic acquisitions
- download and archiving of raw data (scans and photographs)
- pre-processing of raw data (colour allocation to scans and radiometric correction of photos)

Fig. 9.7 3D processing from point cloud—zenith view

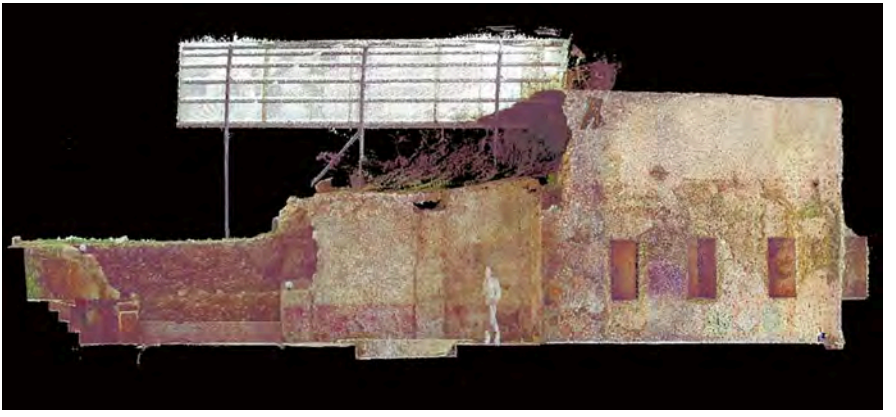

Fig. 9.8 3D processing from point cloud—longitudinal section

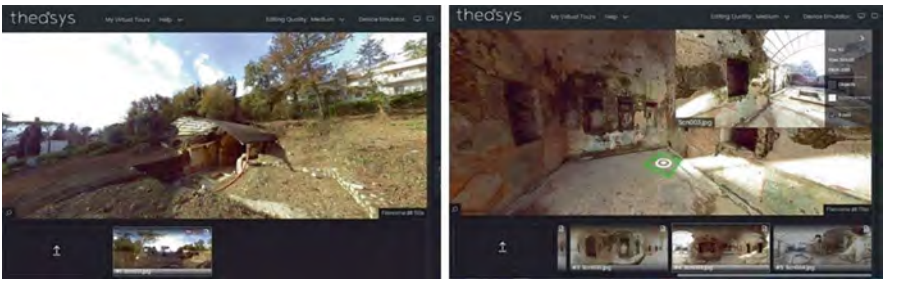

Fig. 9.9 Virtual Tour 2.5D processing by Theasys

Fig. 9.10 QGIS cartographic processing from Open Street Map

Table 9.2 Outputs and tools

Scale of representation, resolutions	Graphics Rapp.: 1:100; 1:50; 1:20 Resolution of three-dimensional models Diagnostics, Structures
Expected outputs	Orthogonal projection drawings (plans, elevations, sections) Thematic mapping Surface models Diagnostics, Structures
Instruments (HD/SW)	Instrumentation available at the DART and LaRSArA laboratories, together with the instrumentation available at the collaborating structures (ENEA, LAPS and LaGGS laboratories of UNICAS, CRITEVAT UNIROMA Sapienza laboratory

- alignment of scans
- photogrammetric processing
- panoramic photo acquisition
- virtual tour processing with 2.5D model
- realisation of a GIS web model with inclusion of digital twin and collected data
- realisation of the expected deliverables
- setting up of monitoring systems and procedures (Table 9.2).

9.4 Results and Discussion

The Ponari Nymphaeum, with its rectangular hall structure and nine square niches, represents an important example of how Roman aristocratic families integrated rooms dedicated to rest and pleasure within their dwellings (Polito, 2013). The walls, initially decorated with rustic mosaics that recalled caves and caverns, were later covered with painted plaster imitating marble, evidence of the evolution of taste in Roman times (Valenti, 1992, 1994; Falzone, 2007). The atrium in front, with its impluvium marble basin, was paved with a white mosaic and decorated with paintings simulating a garden (*paradeisos*) and an isodomic wall apparatus, creating an elegant and refined atmosphere (Betori, 2009; Betori et al., 2009). The presence of the atrium, together with its function as a summer *coenatio*, makes the Ponari Nymphaeum unique in its kind, distinguishing it from the more common type of nymphaeum as an independent structure.

Following the recent cleaning of the decorative apparatus, it is now possible to assess more carefully the state of conservation of the artefact and the criticalities caused by the lesions on the nymphaeum structure, in order to plan the conservation actions to be undertaken on the archaeological asset and the possible preparations to be made for its preservation (Caponero et al., 2020, 2021; Modoni et al., 2022).

9.5 Future Works

The Ponari Nymphaeum represents an important example of Roman residential architecture. Its different building and decorative phases, together with the richness of its mosaics, provide valuable information on the history of Cassino and its territory (Polito, 2013; Tanzilli, 2016). The polychrome floor of the Nymphaeum could prove fundamental in clarifying certain doubts concerning the different phases of its history (Betori & Vincenti, 2017). For this reason, in agreement with the Soprintendenza Archeologia, Belle Arti e Paesaggio for the provinces of Frosinone and Latina, an exploratory survey will be conducted. In addition, upon closer examination, the polychrome floor shows a series of ancient renovations, and it would therefore be useful to carry out a mapping of the floor, highlighting the restorations carried out.

In summary, the following future operational steps are identified:

- Integrated Structural Materials Investigation: Perform an in-depth and integrated analysis of structural materials, in order to understand their nature, physical-mechanical characteristics and degradation conditions, through non-destructive investigations and techniques.
- Define, analyse and catalogue critical processes and risks, both natural and man-made. Identify and analyse all critical and risk processes that threaten the integrity of the archaeological asset, considering both natural factors (such as erosion, earthquakes, atmospheric phenomena) and anthropic factors (such as vandalism,

urbanisation or tourism activities). Cataloguing these risks to develop mitigation strategies and preventive management plans, ensuring the long-term preservation of the site.

- Completing the Post-Processing Phase. Complete the post-processing process of the data collected during the survey and investigation activities to convert this information into a useful and usable format. This step includes the validation, systematisation and organisation of the data into appropriate databases for future analysis and conservation work.
- Implementation of the creation of Digital Models (Virtual Twins). Develop digital models of the Nymphaeum, acting as virtual twins, to accurately replicate the object and allow for detailed analyses, simulations of conservation interventions, and the dissemination of knowledge about the site. Such models are essential to monitor the evolution of the condition of the property and to engage the public through interactive visualisation tools (Gallozzi et al., 2017).
- Preparation of Multi-Criteria Monitoring Procedures. Define and implement multi-criteria monitoring procedures to continuously assess the state of conservation. These procedures should include monitoring of structural, environmental conditions and risk factors, through the integration of advanced sensing techniques (such as environmental sensors and remote sensing technologies) to obtain a holistic view of site dynamics (Caponero et al., 2020, 2021; Modoni et al., 2022).

9.6 Available Metadata and Paradata: Sources of Exchange

For the realisation of the 3D model, the integrated laser scan and photogrammetry survey technique was adopted, which makes it possible to acquire the geometric data and the material/decorative components of the artefact being researched (Gallozzi et al., 2017).

The data available to date, which are currently being processed, are those derived from the survey campaign carried out in 2020, born out of the collaboration between DART (Laboratory for the Documentation, Analysis, Survey and Technique of Architecture) and CRITEVAT (Centre for Research on Engineering for the Protection and Enhancement of the Environment and Territory).

In order to permanently monitor the structures for possible deterioration, the data of the survey campaign carried out by ENEA (Frascati research centre) in collaboration with the LAPS of the University of Cassino and Southern Lazio was acquired; the survey was aimed at mapping the state of the cracking framework, also documenting the areas attacked by mould and lichens, the presence of gaps and detachments, and the qualitative state of the colouring (Caponero et al., 2020, 2021).

The geotechnical monitoring was carried out with the cooperation of the LAGGS of the University of Cassino and Southern Lazio (Modoni et al., 2022).

The Ponari Nymphaeum, like many other archaeological structures, is exposed to various natural and man-made hazards that may threaten its integrity and

conservation. Among the natural hazards, landslides and soil erosion pose a significant danger, especially considering its embedded position in the slope. Weathering, including heavy rainfall and temperature variations, can damage decorations and wall structures, compromising the mosaic and painted plaster. In addition, climate change may accentuate these risks by increasing the frequency and intensity of extreme weather events, such as floods and droughts, which may compromise the stability of foundations and the microclimate of the environment.

On the other hand, anthropogenic risks include the impact of tourism, which can cause physical wear and tear and direct damage to structures, as well as potential environmental contamination. Fortunately, there are no modern structures in the vicinity that could affect the local ecosystem and archaeological context, altering drainage conditions and increasing the risk of water infiltration.

To address these risks, it is crucial to implement sustainable management strategies, including monitoring and conservation programmes, to protect the Ponari Nymphaeum and ensure that this important historical site can be enjoyed by future generations (Modoni et al., 2022).

For the assessment of anthropogenic and environmental risks, a spatial-scale GIS model was chosen. GIS systems allow for the acquisition of varied data in terms of both format and quality aspects. In a first step, a data/attribute grid will be created for the construction of a QGIS model based on overlay mapping, after which the model will be published and shared online (Pierdominici, 2020).

References

Betori, A. (2009). Cassino, novità dal Ninfeo Ponari. La pavimentazione dell'atrio. In *AISCOM XIV* (pp. 195–199).

Betori, A., & Vincenti, V. (2017). Nuovi pavimenti dalla Domus del Ninfeo Ponari di Cassino. In *AISCOM XXIII* (pp. 447–459).

Betori, A., Valenti, M., & Tanzilli, S. (2009). Ninfeo Ponari di Cassino: Nuove acquisizioni e prospettive di valorizzazione. In G. Ghini (Ed.), *Lazio e Sabina 5* (pp. 483–498). Atti del convegno Quinto Incontro di Studio sul Lazio e la Sabina.

Caponero, M. A., Corsi, C., Mongelli, M., Imbimbo, M., Polito, E., Modoni, G., & Grande, E. (2020). Tecnologie per il monitoraggio strutturale del Ninfeo Ponari di Cassino. Una sperimentazione in collaborazione tra ENEA ed Università di Cassino. In C. Arcangioli & M. S. Sarto (Eds.), *Centro di eccellenza DTC Lazio. Atti del I Convegno annuale (Roma, 30 settembre 2019), Roma 2020* (pp. 69–71).

Caponero, M. A., Mongelli, M., Imbimbo, M., Polito, E., Modoni, G., & Grande, E. (2021). Structural monitoring of the Ninfeo Ponari by fibre optic sensors, photogrammetry and laser scanning. *Archeologia e Calcolatori*, 223–232. CNR, ISSN: 1120-6861.

Carettoni, G. F. (1940). Casinum, presso Cassino. In *Italia romana: Municipi e colonie, s. I* (Vol. II).

Cifarelli, F. M. (1995). Un ninfeo repubblicano a Segni con la firma di Q. Mutius architetto. In *Tra Lazio e Campania. Ricerche di Storia e di Topografia antica* (pp. 159–188). Università degli Studi di Salerno. Quaderni del Dipartimento di Scienze dell'antichità, 16 – Serie Storia Antica e archeologia, II.

Cifarelli, F. M., & Valenti, M. (1999). Due nuovi ninfei decorati nel Lazio meridionale. In *La Mosaïque Gréco Romaine VII, Actes du VII Colloque International pour l'Étude de la Mosaïque Antique, 3–7 octobre 1994, Tunis* (pp. 673–680).

Falzone, S. (2007). *Ornata aedificia. Pitture parietali dalle case ostiensi, Roma*.

Gallozzi, A., Paris, L., & Wahbech, W. (2017). 3D models and interactive communication for archaeology: The Nymphaeum Ponari in Cassino. In *Conference: Digital Archaeologies, Material Worlds (Past and Present)—CAA 2017, Atlanta, GA* (pp. 401–411).

Guiral, C., & Mostalac, A. (2005). Representació d'arbres, flors i plantes en la pintura romana. In J. d'Empupùrie (Ed.), *La jardineria en època romana, Girona* (pp. 53–60).

Modoni, G., Imbimbo, M., Serpe, M., Polito, E., Saccucci, M., Spacagna, R. L., Grande, E., Caponero, M. A., Mongelli, M. L., & Valenti, M. (2022). Geotechnical-structural engineering for the preservation of Ninfeo Ponari in Roman Casinum. In *Engineering for the Preservation of Monuments and Historic Sites III—Proceedings of the 3rd International ISSMGE TC301 Symposium, 2022 Open Access, Napoli 22 June 2022 through 24 June 2022* (pp. 583–594).

Neuerburg, N. (1965). L'architettura delle fontane e dei ninfei nell'Italia antica. In *Memorie dell'Accademia di Archeologia, Lettere, e Belle Arti di Napoli 5, Napoli*.

Pierdominici, F. (2020). La raccolta dati in ambiente QGIS per un modello territoriale nazionale dei ponti antichi. In C. Inglese & L. Paris (Eds.), *Arte e tecnica dei ponti romani in pietra* (pp. 77–100).

Polito, E. (2013). Il complesso archeologico di Cassino: uno sguardo d'insieme nel segno di Ummidia. In P. Gabriella (Ed.), *Studi in ricordo di Gabriella Braga, III, a cura di Marco Palma e Cinzia Vismara* (pp. 1453–1469). Edizioni Università di Cassino.

Tanzilli, S. (2016). *Cassino. Architettura, archeologia, arte, storia*. Formia.

Valenti, M. (1992). Il "Ninfeo Ponari" di Cassino (FR): Analisi stilistica e cronologica delle decorazioni. In *Archeologia Classica XLIV, Roma* (pp. 51–80).

Valenti, M. (1994). Il mosaico rustico a conchiglie e il ninfeo Ponari di Cassino. Riflessioni su una moda decorativa di età tardo-repubblicana. In *AISCOM II* (pp. 49–60).