

# Interdisciplinary Method to Analyze Historical Water Resource Management Systems: the Case Study of *Masseria del Cristo* in Matera, Italy

Daniele Altamura<sup>1\*</sup>, Enrico Lamacchia<sup>2</sup>, Ruggero Ermini<sup>3</sup>, Nicola Masini<sup>4</sup>, Marcello Schiattarella<sup>5</sup>  
1\* – Dipartimento per l’Innovazione Umanistica, Scientifica e Sociale, Università della Basilicata, via Lanera 20, 75100  
Matera, IT, [daniele.altamura@unibas.it](mailto:daniele.altamura@unibas.it)  
2 – Dipartimento per l’Innovazione Umanistica, Scientifica e Sociale, Università della Basilicata, via Lanera 20, 75100  
Matera, IT, [enrico.lamacchia@unibas.it](mailto:enrico.lamacchia@unibas.it)  
3 – Dipartimento per l’Innovazione Umanistica, Scientifica e Sociale, Università della Basilicata, via Lanera 20, 75100  
Matera, IT, [ruggero.ermi@unibas.it](mailto:ruggero.ermi@unibas.it)  
4 – Institute of Heritage Science CNR, C. da S. Loya, 85050 Tito Scaletto (MT), IT, [nicola.masini@cnr.it](mailto:nicola.masini@cnr.it)  
5 – Dipartimento per l’Innovazione Umanistica, Scientifica e Sociale, Università della Basilicata, via Lanera 20, 75100  
Matera, IT, [marcello.schiattarella@unibas.it](mailto:marcello.schiattarella@unibas.it)

## Abstract

The rural architecture of Matera preserves important traces of the historical heritage represented by integrated water resources management systems, which contributed to the inscription of the city on the United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage List in 1993. The need to guarantee water supply led to theoretical and practical knowledge aimed at sustainable management of resources, both within the urban fabric of the *Sassi* and along the historical routes of transhumance. The farmhouse known as *Masseria del Cristo*, in the countryside of Matera, bears historical evidence of this heritage, unlike what is observable in urban areas due to the significant transformations undergone in recent decades. Excavated cisterns, settling tanks, dug channels and a semi-excavated cistern with a roof were detected through photogrammetric processes and represented through 3D digital models that are freely available online. Through the analysis of this specific case study, the contribution proposes an interdisciplinary multiscale method to investigate the relationship between historical water systems and the geomorphological and hydrological context in which said systems are located. The results of this process provide a solid starting point to guide proper practices for the protection, recovery and enhancement of this historical heritage.

**Keywords:** Interdisciplinary Multiscale Analysis, Historical Water Systems, Digital Survey, 3D Virtual Fruition, Rural Architectural Heritage.

## 1. Introduction

Digitalization processes play a central role in scientific research in the conservation and promotion of cultural heritage.

In recent years, the scientific community has shown a growing interest in developing innovative methodologies and techniques for the survey and analysis of detailed historical heritage information. These processes produce results useful for managing, designing and monitoring restoration interventions and functional recovery, as well as for enhancement and tourist promotion [1].

Structure From Motion (SFM) photogrammetric modeling, which uses frames acquired through cameras mounted on Unmanned Aerial Vehicle (UAV) devices, provides an innovative technology capable of returning high-quality information data, through rapid and simplified processes.

51 The photogrammetric survey enables the documentation of historical heritage at risk of disappearing and the  
52 development of 3D digital models for virtual fruition.

53 This study structures a multiscale analysis process to analyze systems of interception, channeling, collection and use  
54 of the water resource of a historical rural building, known as *Masseria del Cristo*, in the countryside of Matera  
55 (Southern Italy), ensuring its virtual enjoyment through online 3D models which represent information banks to  
56 transfer knowledge. The choice of this approach stems from the need to properly know the intrinsic characteristics of  
57 such heritage, which is the product of historical practices aware of the relationship between architectural scale  
58 elements and the wider morphological and hydrological context in which they are located.

59 The *masserie*, historical farmhouses, are complex and heterogeneous architectural organisms, which constitute the  
60 key elements around the agricultural landscape of Southern Italy, organized on the latifundia and transhumance [2-3],  
61 from the Modern Age until the first half of the 20th century.

## 62 2. Methods

64 This contribution presents a methodological approach to study the historical heritage represented by integrated  
65 water resource management systems in the area of the *Masseria del Cristo*, in Matera. The analysis of these systems,  
66 inserted in a rural context, which generally have not transformed as in urban areas, provides a systematic knowledge  
67 of traditional water supply practices and techniques. The proposed methodology permits to study this heritage  
68 through a multiscale interdisciplinary workflow, because the study of water resource management systems requires  
69 an extended sight at the natural environment in order to understand the close link between human settlement,  
70 morphology and hydrology of the territory.

71 Rural architecture constitutes a substantial and invaluable component of the built heritage, not only within the  
72 boundaries of the case study presented but across the entire Italian territory. Until the aftermath of the Second World  
73 War, Italy remained a predominantly agrarian society. Consequently, the countryside was not only inhabited but also  
74 actively shaped and experienced, often even more intensively than urban areas. This historical condition, which finds  
75 parallels in many other European countries, gave rise to an exceptionally rich and diverse architectural landscape. The  
76 buildings that populate this landscape draw their distinctive features from a profound and enduring relationship with  
77 the surrounding environment.

78 The case study examined in this research was selected precisely because it embodies this legacy, offering an  
79 exemplary testimony to the ingenuity and skill of early builders. These individuals, despite the absence of modern  
80 tools and technologies, were remarkably capable of reading the landscape, harnessing local resources, and making  
81 thoughtful decisions about where and how to establish a settlement. Their choices reflect a sophisticated  
82 understanding of environmental conditions and reveal an inherent sustainability in their approach to construction.

83 The methodology developed in this study is based on a multi-scalar analysis that considers both the architectural  
84 artefact and its broader territorial context. This is achieved through the combined use of different technologies,  
85 including UAV devices for detailed architectural surveys and Geographic Information Systems (GIS) for large-scale  
86 spatial analysis. The latter makes use of data provided by various public administrations, enabling a broader  
87 understanding of the landscape dynamics at play.

88 Although each heritage site possesses its own unique characteristics, the proposed method proves effective in  
89 identifying the common features that define historical rural architecture. These features consist of a body of  
90 knowledge, practical expertise, and experiential wisdom that have been accumulated over centuries, allowing  
91 communities to develop meaningful and adaptive relationships with the natural environment.

92 By integrating archival and bibliographic research with architectural surveying, geomorphological and hydrographic  
93 analysis of the surrounding landscape, this study offers a comprehensive and interconnected reading of the built  
94 heritage. The resulting interpretation highlights causal relationships between the various factors involved, making it  
95 possible to understand the rationale behind past settlement and construction choices. These insights remain highly  
96 relevant today, providing valuable guidance in an era when environmental sustainability has become an essential goal  
97 for contemporary planning and design.

98 The proposed methodology is structured in the following steps:

- 99 1. *A bibliographical and archival search* that provides relevant information on the subject. The bibliographic  
100 search gives a global knowledge of the heritage under study and can provide interesting ideas for the  
101 analysis. At the same time, the information acquired through the consultation of historical archival  
102 documentation represents a necessary starting point for the next steps.
- 103 2. *State-of-the-art surveys* to acquire an accurate basis on which to carry out the analysis of the historical  
104 integrated water management systems.
- 105 3. *An interdisciplinary multiscale analysis* structured in two consequential steps of territorial and architectural  
106 research, allowing the case study to be framed within a larger area, identifying the close link between

107 geological, morphological and hydrological characteristics and the integrated water resource management  
108 systems. The outcome concerns the detailed study of the different components of the system and their  
109 interrelations on an architectural scale.

110 4. *Open source virtual fruition*, made possible by selecting a platform on which to implement the 3D model  
111 generated in the previous steps, which can be freely accessed by users without any cost.

## 112 2.1 Bibliographical and archival research

113 The study of the bibliography was conducted through the consultation of scientific databases of Scopus,  
114 ResearchGate, Google Scholar and supported by the study of unindexed works related to the so-called *grey literature*.  
115 This phase enabled the acquisition of an in-depth understanding of the entire structure and the territorial context in  
116 which it was originally conceived. On the one hand, the consulted literature provided valuable insights into the  
117 morphological and geological features of the *Gravina di Picciano*, thus supporting the development of the scientific  
118 reflections presented in the subsequent methodological steps; on the other hand, it offered specific historical  
119 information regarding the evolutionary phases of the *masseria* and the functioning of the associated integrated water  
120 management systems.

121 The analysis of documentation enabled the validation of the historical information gathered through bibliographic  
122 research and its integration with new insights. This step was conducted through the consultation of several local  
123 archives, such as the State Archive of Matera (*Archivio di Stato di Matera*), the Diocesan Archive of Matera  
124 (*Archivio Diocesano di Matera*) and the RSDI Basilicata (Regional Spatial Data Infrastructure of the Basilicata  
125 Region) [4] online web platform. This step provided a solid basis for the analysis of this heritage and its  
126 characteristics in order to plan the survey and the analyses carried out at both territorial and architectural scales.

127 The *Masseria del Cristo*, or *Santissimo Sacramento*, stands on the *Piano di Gnatamura*, a plain area about 10 km  
128 west of the urban center of Matera, along a secondary branch of the ancient route from Matera to the Sanctuary of  
129 *Santa Maria di Picciano*, part of a vast network of historical farms and *jazzi* (typical structures for breeding and  
130 sheltering sheep) [5].

131 This architecture is located in the environmental context of the *Gravina di Picciano* stream, a left tributary of the  
132 *Bradano* river. The landscape is characterized by the contrast between the harsh bare limestone rocks along the steep  
133 banks of the stream and the clay cultivated with extensive arable land and olive trees. The *masseria* is located on a  
134 rocky outcrop exactly on the border between the limestone and clay, a few meters from the edge of the *Gravina*.

135 The historical sources related to the *Masseria del Cristo* appear limited, but they testify to its different  
136 configurations over time. Ancient documents call this district *Vocuzza*, or *Bocuzza* [5]. In this place, the *masseria*  
137 already appears at the beginning of the 17th century as a property purchased by the *Paolicelli* family, together with  
138 other possessions constituting a large estate, from the previous owner *Giacuzzi* family, which attests to its previous  
139 realization [6].

140 The probable original configuration of the building is stated in a document dated 11th September 1700 and released  
141 by the public officer (*tabulario*) of the city of Matera, *Don Giacomo Antonio Casamassima*. In this report, the manor  
142 is described as a farmhouse made up of a single brick slab with a pitched roof, a fireplace, an adjacent well and three  
143 enclosed courtyards. Construction began in 1706, when ownership passed from the *Paolicelli* family to the  
144 Confraternity of the *Santissimo Sacramento* of the Cathedral of Matera [6].

145 The building, used until the mid-20th century, preserves multiple traces of historical construction techniques and  
146 ingenious integrated water management systems. The peculiar characteristics and the critical state of conservation  
147 and accessibility, as well as the serious risk of definitively losing this heritage, motivated the choice of the case study.

148 This *masseria* shows itself in an almost unchanged condition, unlike what can be found in the historical urban fabric  
149 of the *Sassi*, significantly transformed during the recent decades.

## 150 2.2 Digital Survey

151 The state-of-the-art analysis is a necessary action to understand the parts that compose a historical building, their  
152 characteristics and how they interact to enable the functioning of the whole artifact. The use of innovative technologies  
153 for the geometric survey ensures short acquisition times and high precision. For this reason, this study opted to use  
154 UAV photogrammetric and traditional survey techniques.

155 This step needs to be remotely programmed through the integrated software of the drone used or other external  
156 software. The on-site survey is carried out only afterwards. To improve the accuracy of the survey, well visible markers  
157 for ground control points (GCPs) must be provided. The GCPs shall be evenly distributed in the survey area and well  
158 anchored to the ground, and they are intended to constitute the reference for aligning and georeferencing the data  
159 acquired. The above images are processed in specific software to obtain point clouds, which are further processed for  
160 the purpose of generating 3D digital models. Photogrammetric processes require careful acquisition of the frames,  
161 respecting the following parameters and precautions, for ensuring a successful acquisition and an accurate  
162 reconstruction of 3D models.

163 After acquiring all the information necessary to understand the subject, the authors conducted an on-site inspection.  
164 The preparation of this investigation directly affects the quality and accuracy of the data that will be collected  
165 subsequently.

166 A preliminary site survey was essential to identify potential interference and disturbance elements that could have  
167 adversely affected the acquisition phases. The accessibility of the site, the physical access to the area, the  
168 environmental and lighting conditions were assessed (natural lighting should be evaluated to avoid strong shadows and  
169 light variations that can complicate image processing) and finally the possible presence of disturbing elements such as  
170 crowds or moving elements which could interfere with the instrumentation used in the acquisition step.

171 Photogrammetric acquisition with UAV necessarily included the consultation of d-flight flight maps to verify  
172 airspace categories and determine any restrictions or permits required. The survey was remotely programmed through  
173 the integrated software of the drone Autel Robotics Evo II 6K [7], with which the photogrammetric in situ survey was  
174 subsequently conducted. To improve the accuracy of the survey, well visible markers have been set up for GCPs.

175 The GCPs were evenly distributed in the survey area and well anchored to the ground and served as reference  
176 for aligning and georeferencing the data acquired. The acquisition of the frames has respected the following parameters  
177 and devices, ensuring the accurate reconstruction of the 3D models: frame overlap between 60% and 80% both on  
178 longitudinal and transverse axis; different camera inclinations, enabling the capture of details that otherwise would  
179 remain in shadow; manually setting of shutter settings, such as aperture, exposure time and ISO, which must be  
180 managed manually to ensure uniformity of image exposure; use of frames in their original entity, without cropping or  
181 resizing operations.

182 The survey with drones has affected the factory of the farm and the external areas of relevance, for a total area of  
183 about 30,000 m<sup>2</sup>, where a series of structures aimed at integrated management of water resources have been identified.  
184 The survey included a first UAV photogrammetric survey and a second traditional survey.

185 The first one enabled the capture of 1132 frames (Fig. 1) and was conducted in the following steps:

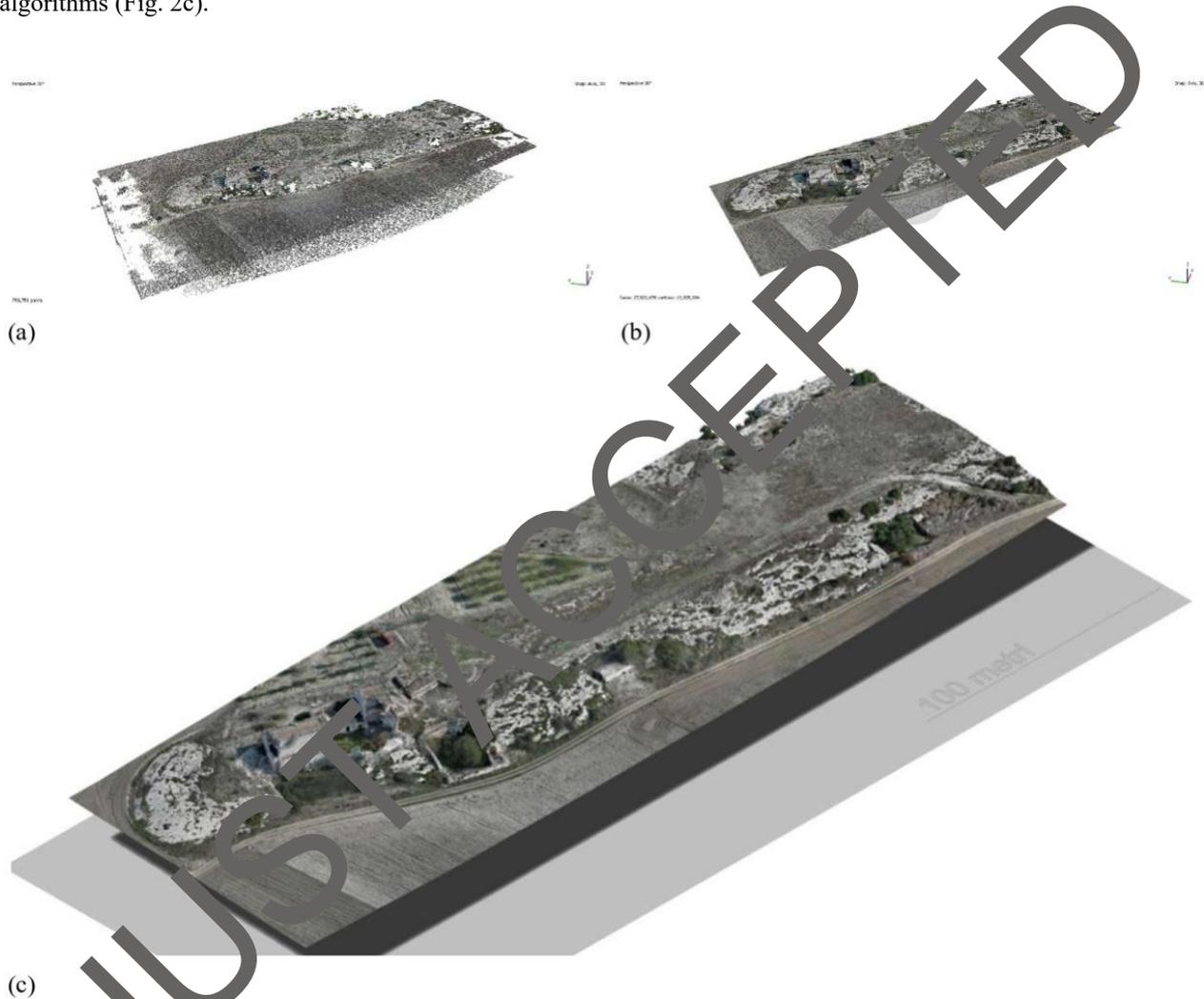
- 186 1. Automated flight at 50 m from the level of the road access to the area, through which it was possible to obtain  
187 photos of context at the territorial scale, with a time of acquisition equal to about 10 minutes;
- 188 2. Automated flight at 40 m from the level of the access road to the area of the farm with photographic overlap of  
189 80%, rectangular grid and zenith camera, with a time of acquisition of about 20-25 minutes;
- 190 3. Automated flight at an altitude of 20 m from the level of the access road to the area of the farm with a  
191 photographic overlap of 60%, rectangular grid and camera with inclination of 45° and with a time of  
192 acquisition of about 15-20 minutes;
- 193 4. Manual flight of detail at 5-10 m above the level of the road to the area of the *masseria* with a zenith camera  
194 and inclined at 45°, with a scan time of about 20 minutes.



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198 Fig. 1. Aerial photography with UAV of the *Masseria del Cristo* at 40 m above the level of the access road to the area.  
199 © 2025, Daniele Altamura, Enrico Lamacchia

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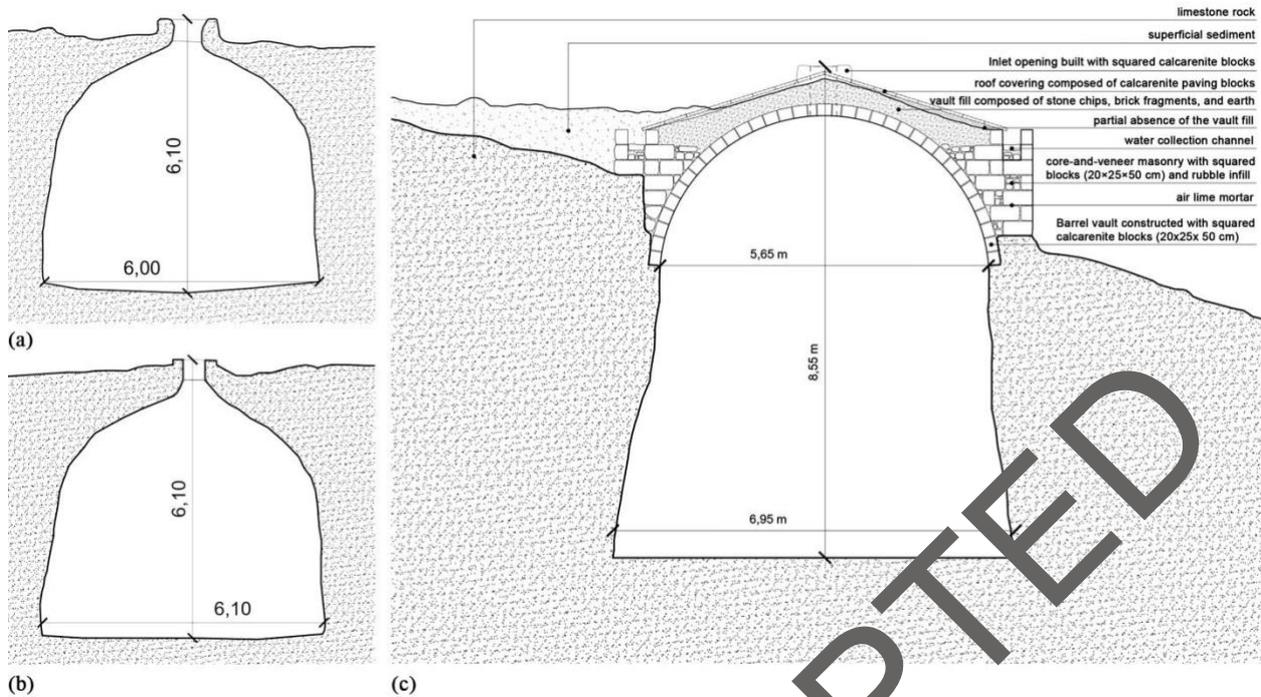
The frames acquired through the previous photogrammetric survey step were processed in order to obtain a point cloud, which was in turn processed through the use of Agisoft Metashape software [8], following a series of basic preparatory steps to extract geometric information from photographs. The images acquired with the drone, as raw as possible and without distortion corrections, were imported into this software, which identifies common points in photographs, calculates, and determines the camera position for each image and optimizes the camera's calibration parameters. The result of this process is a "sparse point cloud" and a series of camera positions (Fig. 2a), which afterwards has been processed to obtain the "dense point cloud" (Fig. 2b), necessary for the generation of the 3D mesh (Fig.2c). Before the generation of the mesh, manual cleaning tools have been used to remove gaps in the reconstruction of the 3D model and correct anomalies. The mesh generation step is the process by which the previously obtained point cloud is transformed into a detailed and optimized 3D mesh using advanced triangulation algorithms (Fig. 2c).



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Fig. 2. Sparse point cloud (a), dense point cloud (b), 3D mesh (c) in Agisoft Metashape. © 2025, Daniele Altamura, Enrico Lamaccina.

The inaccessibility of the cisterns excavated into the rocky substrate (Fig. 3), due both to the limited size of the intake openings and to their precarious state of preservation, has precluded the use of instrumental survey techniques employing drones or Light Detection And Ranging (LiDAR) systems, both of which require the physical presence of operators within the cistern itself. Consequently, the dimensions of the structures were derived through traditional survey methods using a laser distance meter and applying the triangulation technique. The data obtained reveal dimensions and typological features consistent with those of other similar artifacts found in the area, reflecting construction practices and techniques deeply rooted in the local building tradition [9].



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(a) (b) (c)  
Fig. 3. (a-b) Technological sections of the two “a campana” cisterns. (c) Technological sections of the “a tetto” cistern. © 2025, Daniele Altamura, Enrico Lamacchia.

### 2.3 Interdisciplinary multiscale analysis

To properly understand the intrinsic characteristics of any artefact, it is necessary to look at the context in which it is placed. Similarly, a thorough study of the architectural heritage requires a careful reading of its territorial context.

In the anthropic settlements of this area, the shapes of places guided practices aimed at supplying the resources necessary for survival and water management, leaving indelible traces that bear witness to the technical knowledge of the ancient inhabitants. The presence of complex integrated water resource management systems has led to a methodology that highlighted the relationships between geology, morphology and surface rainwater runoff, enabling the understanding of the path of the surface water and the mechanisms of water resource accumulation.

A multiscale approach was adopted to analyze the functioning of the integrated water resource management system and thus the interrelations between its different components.

The hydrographic analysis was carried out using QGIS software [10], and a model was developed in the GIS environment. Surface runoff accumulation maps were produced starting from the DTM data made available by the RSDI *Basilicata* platform [3]. This analysis permitted the comprehension of the mechanisms of water storage in the tanks, the configuration and operation of the individual components of the system and their interrelations.

The area of Matera can be considered the “physical boundary” between the Matera-Laterza Horst [11] to the north-east (*Murge* is the geographic name of this type of flat-topped carbonate hills in the Apulian district) and the bas-relief landscape molded in the clays of the foredeep to the south-west [11]. Further, this landscape is characterized by the presence of deep and narrow V-shaped valleys and/or gorges in the strict sense (i.e., with vertical sides), named *gravine* [12, 13]. The *Masera del Cristo* is located on a limestone outcrop 10 kilometers from Matera town, at an altitude of 250 m above sea level, not far from the *Gravina di Picciano* stream (Fig. 4).



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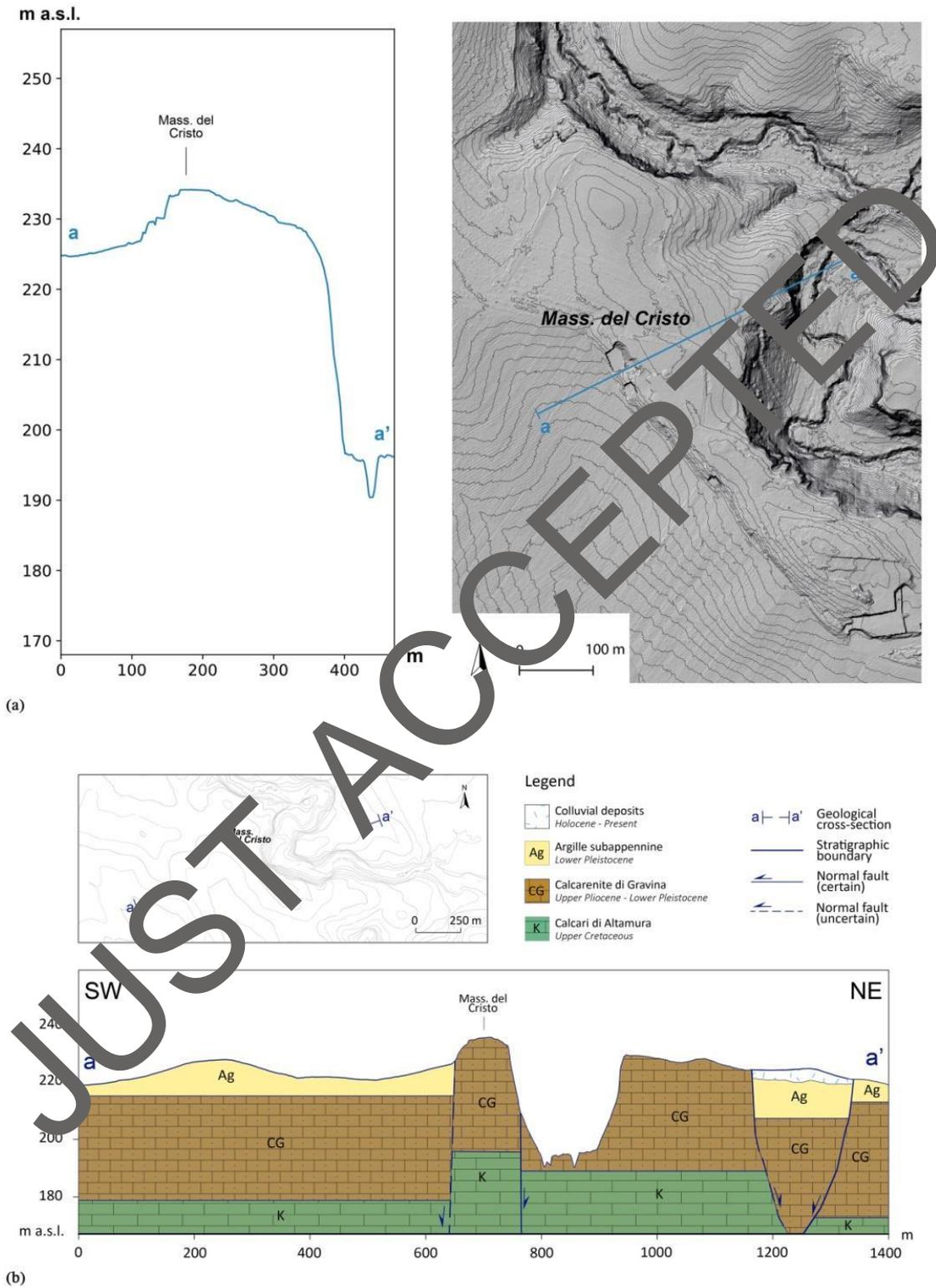
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Fig. 4. (a) Aerial photography of the *Masseria del Cristo* territorial context and access route from the town. (b) Aerial photography of the site. (c) Framing of the *Masseria del Cristo* with geographic coordinates of the artifact, the *calcarenita* outcrop and the *Gravina di Picciano* stream. © 2025, Daniele Altamura, Enrico Lamacchia.

From a geological viewpoint, the study area is entirely included in the foredeep domain (*Fossa Bradanica*) of the southern Apennines, filled by a marine regressive stratigraphic succession made of clay, sand and conglomerate (from the bottom to the top), early Pleistocene in age. In the surroundings of *Masseria del Cristo*, the clay formation (*Argille subappennine*) is largely outcropping, locally covered by a few meters-thick eluvial-colluvial deposits. This formation stratigraphically overlies the bioclastic limestone of the *Calcarenita di Gravina*, late Pliocene - early Pleistocene in age, cropping out along the sides of the canyon in which the *Gravina di Picciano* stream flows. Out of the gorge, the *calcarenita* emerges exclusively in correspondence with the elongated relief trending Northwest-Southeast, upon which the *Masseria del Cristo* is situated.

Along the *Gravina di Picciano*, about 5-6 km to the south, the clastic limestone unconformably lies on the Upper Cretaceous limestones *Calcari di Altamura*, which constitutes the geological backbone of both the morphostructural plateau of *Matera* and the whole Apulian foreland. Since the *Calcarenita di Gravina* does not exceed 30-40 m in thickness in the investigated area, a geological cross-section through the site can easily show the entire stratigraphic

267 sequence, here affected by normal faulting [11, 13]. Indeed, the geological and geomorphological analysis reveals the  
268 presence of a set of Northwest–Southeast oriented faults, which are responsible for the genesis of the flat spur on which  
269 the *Masseria del Cristo* stands, and which have shaped the distinctive morphology of the area selected for the  
270 construction of the structure (Fig. 5).



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272 Fig. 5. (a) Morphology of the area of *Masseria del Cristo*. (b) Geology of the area of *Masseria del Cristo*. © 2025,  
273 Marcello Schiattarella, Lucia Contillo.  
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275 Some straight fluvial segments of the *Gravina di Picciano* stream display the same orientation (as, for example, the  
276 stretch immediately to the south of the limestone hump of *Masseria del Cristo*), being controlled by the same fault



289 The hydrographic analysis carried out using QGIS software, based on the DTM data provided by the Basilicata  
290 Region through the online RSDI *Basilicata* platform, revealed that the cisterns were built in correspondence with the  
291 probable underlying Direct Fault. These cisterns collected meteor water carried by the western waterproof clay surfaces  
292 of the Mountains of *Carbone*, *Picciano* and *Timbro*. The produced maps highlighting the relationship between  
293 morphology and surface runoff of the meteor water explain the reasons behind the choice of the site for the  
294 construction of the *Masseria del Cristo*. In fact, this building is located on the watershed of the corresponding  
295 hydrographic basin, and its position has allowed it to avoid flooding phenomena related to heavy rainfall and to ensure  
296 an extended view to control the surrounding territory (Fig. 7).  
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299 Fig. 7. (a) Aerial photography of the *Masseria del Cristo* area. (b) Aerial photography with superimposed topographic  
300 CTR map (*Carta Tecnica Regionale* at the original 1:10,000 scale). (c) Morphology and stream. (d) Morphology,  
301 *Gravina di Picciano* stream and hydrospatial network. © 2025, Daniele Altamura, Enrico Lamacchia.  
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303 Starting from the analysis and surveys carried out, the subsystems of channeling, collection and use of the resource  
304 were identified, which by using the morphology of the places guaranteed the water supply (Fig. 8). Rainwater is  
305 collected on the surface of bare limestone rock, in which channels of variable length are dug, between 20 and 50 cm  
306 wide and between 10 and 20 cm deep. These channels convey the water to storage “settling tanks” excavated in a  
307 parallelepiped shape of variable dimensions (Fig. 8). Maintenance and cleaning were carried out by removing the  
308 sampling mouth itself.

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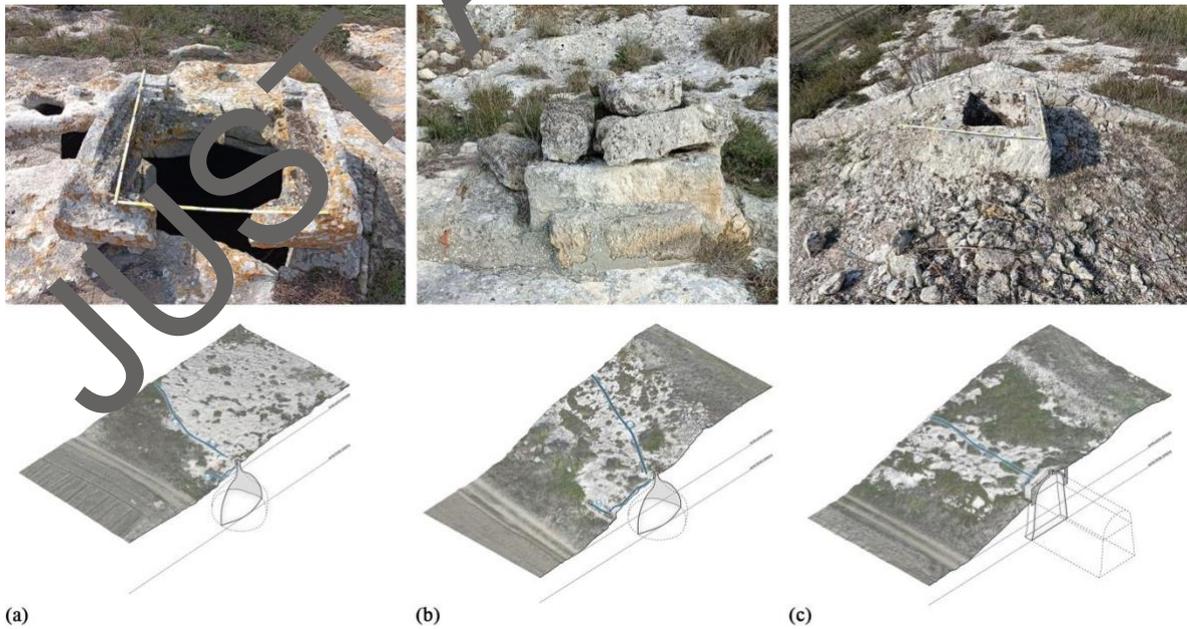


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311 Fig. 8. Plan, elevations and sections of the integrated water resources management system and analytical graphs of  
312 the interception, channeling, collection and use subsystems. © 2025, Daniele Altamura, Enrico Lamacchia.

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314 The clarified water is subsequently transferred through smaller dug channels to three cisterns with an average depth of 6  
315 m. There are two *bell-type cisterns* (Fig. 9a,b) and one *semi-hypogeal with roof cistern* (Fig. 9c).

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318 Fig. 9. (a-b) Schematic axonometric split of the *bell-type cisterns*. (c) Schematic axonometric split of the *semi-*  
319 *hypogeal cistern with roof*. © 2025, Daniele Altamura, Enrico Lamacchia.

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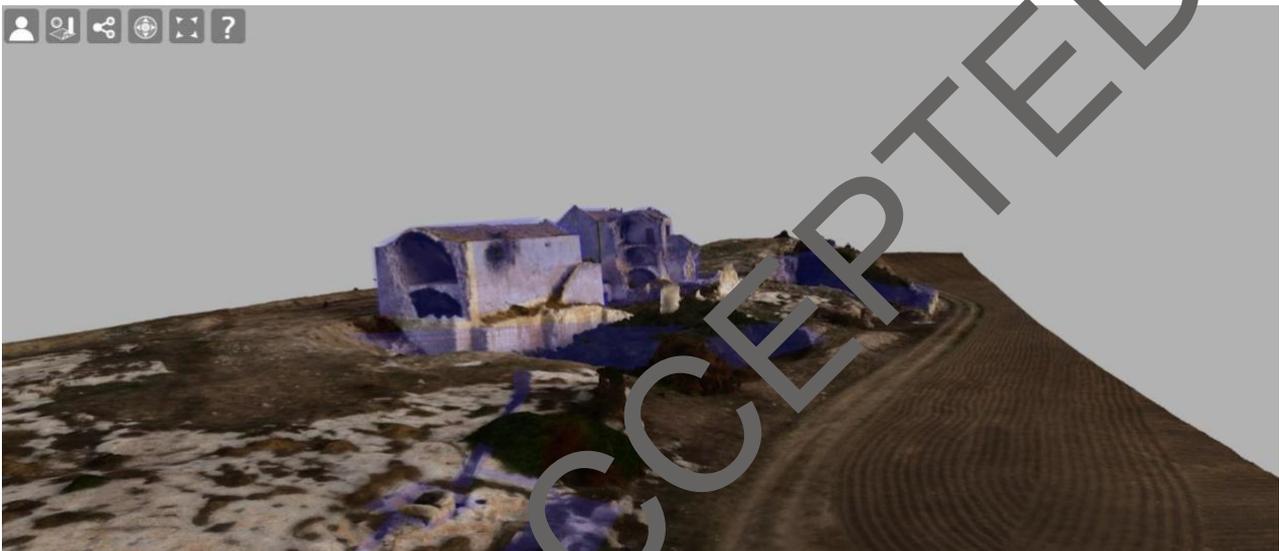
321 The use of the resource occurred through direct withdrawal from the upper mouths using buckets lowered manually  
322 from above. The two *bell-type cisterns* have an additional duct downstream of their mouth, which transfers excess  
323 water through a canal to the drinking trough excavated for animals.

#### 324 2.4 Open source virtual fruition

325 The 3D model obtained through the processes described so far, as well as being functional to this specific study, is  
326 suitable for methods of enhancement and virtual fruition of this heritage.

327 In this way, an inaccessible heritage can be explored remotely through a virtual museum experience. Therefore, it was  
328 decided to upload it to the ATON open-source platform [15], created by the CNR (National Research Council), which  
329 allows users to visualize the model and interact with it in a virtual reality environment (Fig. 10).

330 These tools offer an immersive approach to cataloguing material heritage for scholars and technicians and, at the  
331 same time, easy and engaging dissemination to a broad and non-specialized audience. Dissemination in this form is a  
332 starting point for raising awareness on the topic of heritage at risk and a guide for valorization processes [16].  
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335 Fig. 10. Navigation screen in ATON web platform: 3D model with highlighted selectable elements. © 2025, Daniele  
336 Altamura, Enrico Lamacchia.

### 337 3. Discussions

338 In a general context in which the matrix of architectural shapes has been, for centuries, the adaptation to the natural  
339 substrate, each episode has evolved, starting from common practices, towards peculiar solutions. Understanding  
340 settlement phenomena on a territorial scale cannot therefore ignore the in-depth analysis of the individual pieces that  
341 compose it. This gives rise to the need to identify a research methodology, such as the one proposed in this study,  
342 which relates the individual case to its context. The *Masseria del Cristo*, despite the general precarious state of  
343 conservation, shows unaltered examples of systems for interception, canalization, collection and use of water  
344 resources of rural architecture in Matera.

345 The analysis of historical water systems in the rural territory of Matera offers a valuable testimony to an empirical  
346 and profoundly interdisciplinary knowledge, developed and consolidated over centuries within local rural  
347 communities. Despite the absence of formal support from modern scientific frameworks, this vernacular wisdom  
348 proved remarkably effective in harnessing the geomorphological and geological characteristics of the landscape,  
349 thereby ensuring access to the resources needed for the survival and continuity of human settlement. Among these  
350 resources, water undoubtedly played a central and strategic role. This is clearly reflected in the sophistication and  
351 ingenuity of the systems identified through this research, which reveal a deep understanding of the natural  
352 mechanisms governing water circulation. The attention paid to the geological attributes of the context was not  
353 accidental but stemmed from precise empirical observations that guided both settlement choices and construction  
354 practices.

355 In particular, the decision to build the *Masseria del Cristo* upon a *calcarenite* rocky spur appears to reflect a rational  
356 assessment of the site's hydrogeological dynamics. This elevated position, in addition to offering defensive  
357 advantages and visual command over the surrounding territory, provided favorable conditions for intercepting and  
358 collecting rainwater and surface runoff. These processes were facilitated by the selective permeability of local  
359 lithological formations. The rocky spur, due to its form and composition, thus served not only a defensive function

360 but also played a strategic role in water management, confirming the presence of a form of construction intelligence  
361 deeply rooted in the understanding of the environment.

362 Within this context, geomorphological analysis emerges as an indispensable tool for reconstructing the historical  
363 mechanisms of water procurement. The study of rock types and structures, stratigraphic discontinuities, and the  
364 permeability and porosity of lithic materials, along with the identification of infiltration and runoff dynamics, permits  
365 a scientifically rigorous reconstruction of settlement patterns and resource management strategies developed by rural  
366 communities.

367 In contemporary research, geological studies are essential not only for interpreting the hydraulic techniques of the  
368 past but also for evaluating their effectiveness, sustainability, and potential for adaptive reuse in current contexts.  
369 Stratigraphic surveys, petrographic analyses, topographical mapping, and digital hydrological modeling highlight the  
370 functional principles underlying these systems and the interactions between lithological structures and water flows.  
371 When integrated with historical and archaeological data, this knowledge provides a foundational basis for a  
372 comprehensive scientific approach to the preservation, restoration, and enhancement of rural hydraulic heritage.

373 Geology, therefore, not only offers a critical lens through which to interpret historical practices but also serves as a  
374 fundamental instrument for guiding informed and context-sensitive interventions aimed at the recovery, valorization,  
375 and potential reactivation of these systems. This approach aligns with broader goals of environmental sustainability  
376 and cultural continuity.

377 In this sense, the study of such water systems permits the recovery of meaningful fragments of traditional technical  
378 knowledge, as well as contributing to the recognition and appreciation of a form of territorial resilience. This  
379 resilience, shaped through a harmonious interaction with the natural environment, has ensured the long-term  
380 sustainability of rural settlements in the Matera region.

#### 381 4. Conclusions

382 For these reasons, the case study constituted the test bed for validating the proposed multiscale analysis  
383 methodology, which can be replicated for further case studies, providing a solid starting point for recovery and  
384 enhancement practices. Obtaining a 3D digital model and its interactive online use offers a way to involve and raise  
385 awareness even among non-experts on the topic of historical architectural heritage, constituting an innovative method  
386 of teaching and dissemination.

387 The natural evolution of this research points toward the systematic and detailed cataloguing of additional heritage  
388 assets and architectural artifacts located within the same territorial context. These elements are to be examined using  
389 the same interdisciplinary and multiscale methodology adopted in the current study. Such an extension would permit  
390 a more profound understanding of each architectural object, considered in terms of its morphological, typological,  
391 and functional specificity. Furthermore, it would enable a more comprehensive interpretation of the relationships that  
392 these buildings maintain within the broader networks of settlements, hydraulic systems, and ecological structures  
393 embedded in the landscape.

394 This perspective marks a significant conceptual shift. Cultural heritage is no longer seen as a mere collection of  
395 distinct and independent elements, but rather as an organic and interconnected system, deeply rooted in the landscape  
396 and reflecting its multifaceted nature, encompassing historical, physical, environmental, and socio-economic  
397 dimensions. Within this framework, heritage is redefined as a layered and dynamic palimpsest in which each material  
398 component acquires relational meaning, serving as tangible evidence of a long-standing and layered interaction  
399 between human communities and their surrounding environment.

400 This condition of interrelation represents a fundamental characteristic of historical architecture in general, and of  
401 rural architecture in particular. Indeed, the latter embodies a form of deeply grounded construction wisdom that has  
402 been developed over centuries and transmitted across generations. It is an empirical and context-sensitive knowledge  
403 system, through which past builders devised sustainable solutions that were precisely attuned to the locally available  
404 resources and responsive to the geomorphological and climatic specificities of their environment.

405 Once validated within the context of the present case study, this methodological model proves not only to be  
406 transferable but also highly recommendable for application in other territorial contexts. It is grounded in consolidated  
407 processes of scientific inquiry and in technologies that are now widely accepted and employed by scholars,  
408 professionals, and institutional actors. Consequently, it offers promising avenues for broader applications at national  
409 and international levels, promoting an integrated strategy for the interpretation, conservation, and valorization of  
410 cultural heritage and landscapes. This approach is capable of reconciling scientific rigor with technological  
411 innovation and historical sensitivity, thus fostering a more sustainable and informed framework for heritage  
412 management in contemporary scenarios.

#### 414 5. Author contributions

415 Conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing—original  
416 draft preparation, writing—review and editing, visualization, supervision, project administration, funding acquisition.

417 All authors have read and agreed to the published version of the manuscript.

418

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