



DOCUMENTATION AND MODELLING OF A HYPOTHETICAL RECONSTRUCTION OF THE FIRST ROMAN WATERMILL IN HISPANIA

DOCUMENTACIÓN Y MODELIZACIÓN DE UNA HIPÓTESIS DE RECONSTRUCCIÓN DEL PRIMER MOLINO HIDRÁULICO ROMANO DE LA PENÍNSULA IBÉRICA

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Highlights:

- The first Roman watermill in the Iberian Peninsula has been found with all its structural elements, from the imprints left in the stone by the wheel.
- Virtual reconstruction of the first vertical wheel watermill discovered in Hispania has been made.
- An animated video of the hydraulic watermill gears performance has been created for documentation and dissemination.

Abstract:

The accurate graphic survey of an archaeological site is fundamental for its analysis and research. Furthermore, if this site is to be covered by a building and will not be accessible or visible, its documentation is essential, not only to continue with the research, but also to disseminate and enhance the discoveries. An example of this is the *Hoya de los Molinos* archaeological site in Caravaca de la Cruz (Region of Murcia, Spain). This is where the first mark of the wheel of a Roman vertical watermill in the Iberian Peninsula has been found. This fact is crucial because remains of Roman vertical-wheeled watermills have been found across the Mediterranean but not in the Iberian Peninsula. Moreover, the fact that this watermill still has all its structural elements makes this archaeological site in Caravaca de la Cruz very interesting. Due to these facts, it is essential to disseminate this discovery, so that it can be recognized and considered as archaeological and cultural heritage. To that end, the researchers have carried out a three-dimensional (3D) reconstruction of the most characteristic elements, such as the vertical wheel, the gears that allowed grinding the grain, and the building protecting them. A virtual recreation was carried out, based on the historical and building research, which is displayed in an explanatory video. Furthermore, two reproductions were created: one made to scale of the archaeological site with a 3D printer and another one of the hypothetical structure of the Roman watermill. To achieve this result, historians, archaeologists and engineers have collaborated, thus enabling not only its adequate dissemination, but also its accurate documentation, in an inclusive manner. Thanks to all the work that this paper describes, the Roman watermill found in Caravaca de la Cruz can be known, studied and assessed.

Keywords: virtual archaeology; digital archaeology; cultural heritage; documentation; 3D reconstruction

Resumen:

La documentación gráfica y precisa de un yacimiento arqueológico es fundamental para su posterior estudio e investigación. Cuando el yacimiento quede en el subsuelo de un edificio y no sea accesible ni visitable, dicha documentación es imprescindible, no solo para la continuación de la investigación, sino también para poner en valor los hallazgos encontrados. Un ejemplo de ello es el yacimiento arqueológico de Hoya de los Molinos en Caravaca de la Cruz (Región de Murcia, España). En la Península Ibérica se ha encontrado la primera impronta de la rueda de un molino vertical hidráulico de época romana. Este hecho es fundamental por dos razones: la primera es que los molinos hidráulicos fueron utilizados por los romanos, no por los árabes como se creyó durante mucho tiempo (hecho que se ha rebatido gracias a los hallazgos arqueológicos); la segunda es que se encontraron restos de molinos hidráulicos en todo el Mediterráneo, pero no en la Península ibérica. Además, en el yacimiento se hallaron todos los elementos estructurales del molino hidráulico vertical, lo que hace tan interesante este hallazgo. Por los condicionantes descritos es fundamental divulgar el hallazgo para que sea valorado y conocido. Para ello se realizó una reconstrucción tridimensional (3D) de los elementos más característicos, como son la rueda vertical, los engranajes que permitían la molienda de grano y el edificio que los protegía. A tal efecto, se desarrolló una hipotética recreación virtual y se animó en un video explicativo. También se hicieron dos impresiones 3D a escalas diferentes: una de toda la zona estudiada y otra en detalle del molino y sus engranajes. Para realizar todo lo aquí descrito se trabajó con un equipo multidisciplinar que permitió el estudio y reconstrucción adecuados. Historiadores, arqueólogas e ingenieros colaboraron para obtener este resultado haciendo posible, de una manera inclusiva, no solo su correcta divulgación, sino una precisa

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documentación. Gracias a todo el trabajo descrito en este artículo, el molino hidráulico hallado en Caravaca de la Cruz podrá ser conocido, investigado y valorado.

Palabras clave: arqueología virtual, arqueología digital, patrimonio cultural, documentación, reconstrucción 3D

1. Introduction

The accurate graphic survey of an archaeological site is a fundamental tool for its recognition, documentation and study. Moreover, if the site is to be hidden under a building and will not be accessible or visible, but covered (with the proper protection and conservation measures), this graphic documentation becomes essential. In such cases, it is necessary not only to disseminate the results of the archaeological research, but also to properly manage its enhancement. And these archaeological elements can only be known and recognized as Cultural Heritage thanks to the graphic and documental information prepared in a comprehensive and thorough manner.

The archaeological site *Hoya de los Molinos*, in Caravaca de la Cruz (Region of Murcia, Spain), is an example of an archaeological excavation where it is certain, from the very beginning, that the excavated structures will be buried again. Thus, the Directorate-General of Cultural Heritage of the Regional Government of the Region of Murcia obliged the owner of the plot of land to carry out a thorough and accurate graphic survey of the whole site before reburying it.

The work consisted of a 3D accurate survey with 3D laser scanning and digital photogrammetry. This graphic study was designed with a dual objective. Firstly, the archaeological site had to be graphically documented. Secondly, to use this wide graphic information as a tool to develop outreach materials (2D and 3D models, mock-ups, videos...). This would enable the analysis and recognition for the public at large and the use of its accurate documentation for future research (Peña-Velasco, García-León & Sánchez Allegue, 2017; García-León, Sánchez Allegue, Peña-Velasco, Cipriani & Fantini, 2018).

The watermill was moved by water to grind the cereal grain, a basic component of the human diet, for this reason, it has played a fundamental role in the development of rural areas of the world. To understand its dimensions and to be able to make a virtual recreation of the operation of the watermill, it is necessary to graphically document it (Rojas-Sola & López-García, 2007).

The archaeological excavation and all research works carried out have been supervised and coordinated by the archaeologists María Belén Sánchez González and Juana María Marín Muñoz. They have counted on an interdisciplinary team made up of specialists in various fields, such as topography, geophysics with georadar devices, historical and building analysis, and physical carbonation studies, among others (Sánchez González, Marín Muñoz, Sánchez González & García López, 2020). This research has allowed us to document the excavated archaeological structures and to determine that they belong to a Roman watermill. Based on this information, the survey and 3D virtual reconstruction of the site have been carried out with the necessary knowledge and enough guarantees to build a reliable reconstruction.

2. Roman vertical-wheeled watermills

In order to understand the relevance of the archaeological site *Hoya de los Molinos*, we will briefly analyse the characteristics and types of Roman vertical-wheeled watermills.

The vertical waterwheel mechanism is described by the Roman architect, writer and engineer Vitruvius in 40-10 BC. In the second half of the first century AD, Pliny the Elder commented that water-driven wheels were used in much of Italy (Palomo Palomo & Fernández Uriel, 2007). In recent years, various interventions have discovered Roman watermills, which have corroborated the publications (Wikander, 1984; Wikander, 1985) that modified the idea that watermills became commonly used in the Early Middle Ages. These archaeological discoveries reveal that watermills were used in the Roman world, at least, from the 1st century AD, as seen in the map of Figure 1. It shows the distribution of Roman mills documented by the archaeological sites for the last 40 years (Spain, 2008).

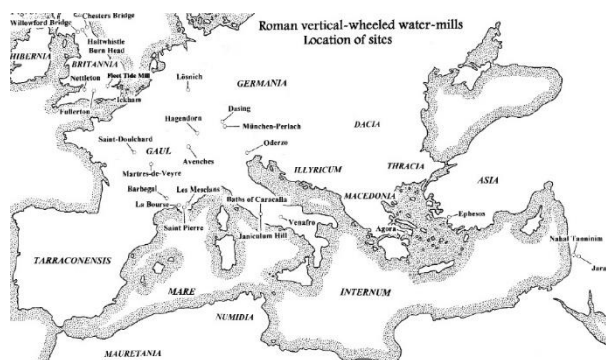


Figure 1: Distribution of documented Roman watermills (Spain, 2008: 13).

Nowadays, mills are known to have existed in the whole Roman world. In the Near East, there is a set of various waterwheels or watermills in Israel, at Caesarea Maritima (Oleson, 1984). In the Italian peninsula, excavations have discovered the mills of the Janiculum, mentioned by Prudentius and Procopius of Caesarea. In 1998, the Aqua Traiana and the complex of watermills parallel to the main channel were excavated on the Roman hill of the Janiculum. At least, five wheels were driven by the Aqua Traiana aqueduct (Wikander, 1979; Wilson, 2000). In the Baths of Caracalla, a mill was constructed at the same time as the baths, around the 3rd century AD. In Venafrò (Jacono, 1938) a waterwheel was discovered. Also in Italy, S. Giovanni di Ruoti (Small & Buck, 1994), from the late 1st century AD.

France and Central Europe are the places where more watermills from the Antiquity have been found. In the east of Arles (southern France), at Barbegal, a Roman complex was discovered, made up of two rows of eight watermills each. By taking advantage of the slope of a gully, they were sequentially constructed, as water stairs. These sixteen watermills were protected by a 60x20 m building. The water supply from Les Alpilles was guaranteed by two aqueducts.

This complex is dated to the second decade of the 2nd century AD (Leveau, 2007). There are more mills in the ancient Gaul: at Les Matres-de-Veyre (Romeuf, 1978) and Mesclans in the French Provence. It seems that the villa of Mesclans was constructed from the late 1st century AD and the early 2nd century AD. Excavations have revealed the complexity of premises located in the surrounding area: an oil mill, a warehouse, a corridor connecting the rooms in the dwelling. Most buildings are laid out in a 38x70 m rectangular complex. They form the *pars rustica* of a villa dedicated to the production of wine, oil and cereals.

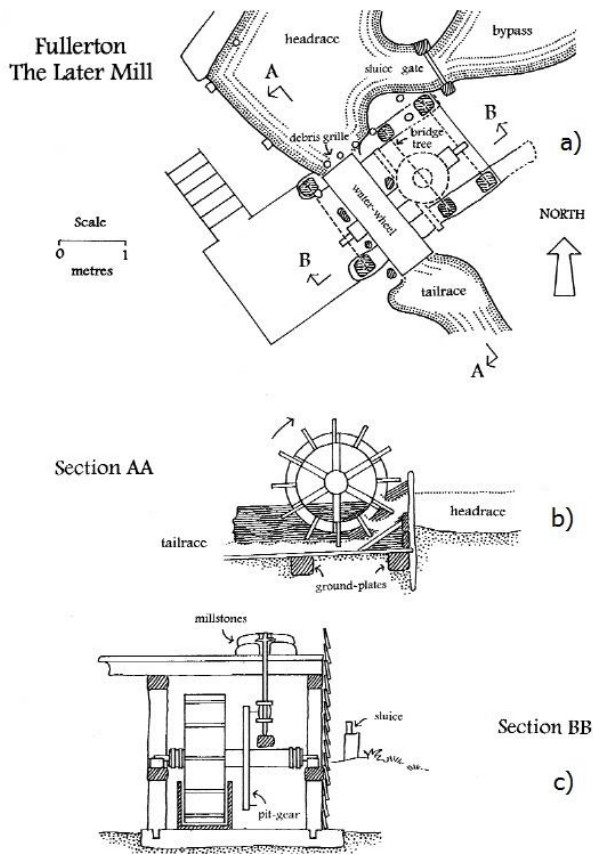


Figure 2: Hypothetical reconstruction: a) ground plan; b) section AA; and c) Section BB) of the mill in Fullerton (Spain, 2008: 27).

In contrast to the factory in Barbegal (maybe exploited by a civil administration), the mill of Mesclans corresponds to private and household use. This mill would have been used to produce flour for the inhabitants of a villa and, maybe occasionally, to supply the near trade routes (a waterwheel about 3 m in diameter). The watermill of Les Laurons, at Ares (France) also depended on a villa: in the centre of a 6x4 km territory, the property of a rich landlord combined his residence and a large farm with a watermill dated in the 3rd and 4th centuries AD (Brun & Borréani, 1998).

In England, at the Fullerton Roman Villa (near Hampshire), the excavations of years 2000 and 2001 discovered a waterwheel (about 2 m in diameter) from the 3rd century AD (Fig. 2), which was subsequently replaced with a narrower waterwheel that proved to be more efficient, both mechanically and hydraulically (Cunliffe & Galliou, 2002).

The Iberian Peninsula was a paradoxical case so far. From all Roman vertical waterwheels found to date, none of them had been discovered in the Iberian Peninsula until 2019. This year, two of them were found: the mill subject matter of this paper, in *Caravaca de la Cruz* (Murcia), and another mill found in the surrounding area of Jerez (Cadiz), at the site of *La Corta*, where a three-mill hydraulic complex has been excavated with three waterwheels, one of them from the Roman period.

This absence may be explained by the reuse and modification of mills, which resulted in the lack of mill remains from that period. That is why this discovery in Caravaca de la Cruz is so interesting.

3. Object of study

The archaeological excavation in the area known as *Hoya de los Molinos*, in Caravaca de la Cruz, started at the end of May 2019 and has documented elements of a watermill initially dated, based on the ceramic materials, between the 1st and 2nd centuries AD. Thus, this would be the first archaeological site in the Iberian Peninsula with a Roman watermill that still has all its structural elements (Sánchez González, Marín Muñoz, Sánchez González & García López, 2020).

This vertical-wheeled watermill would be located in a place that has kept, thanks to the name of the place, the memory of this complex that used the force of water to grind the grain. At this site, two water supply channels stand out, which are relatively parallel (Fig. 3). Both of them are from the Roman period, but the one of the left is secondary. The other one, the main object of this study, supplied the area with water from a spring known as Las Fuentes del Marqués, located in the northwest, at an approximate distance of 1.5 km and at 630 m above

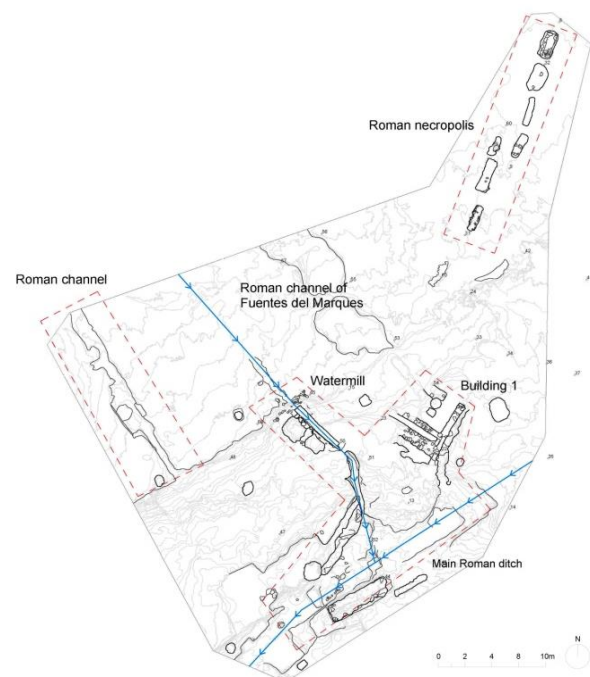


Figure 3: Drawing of the various areas found in the site: the Iberian channel, the Roman channel with the mill and the necropolis.

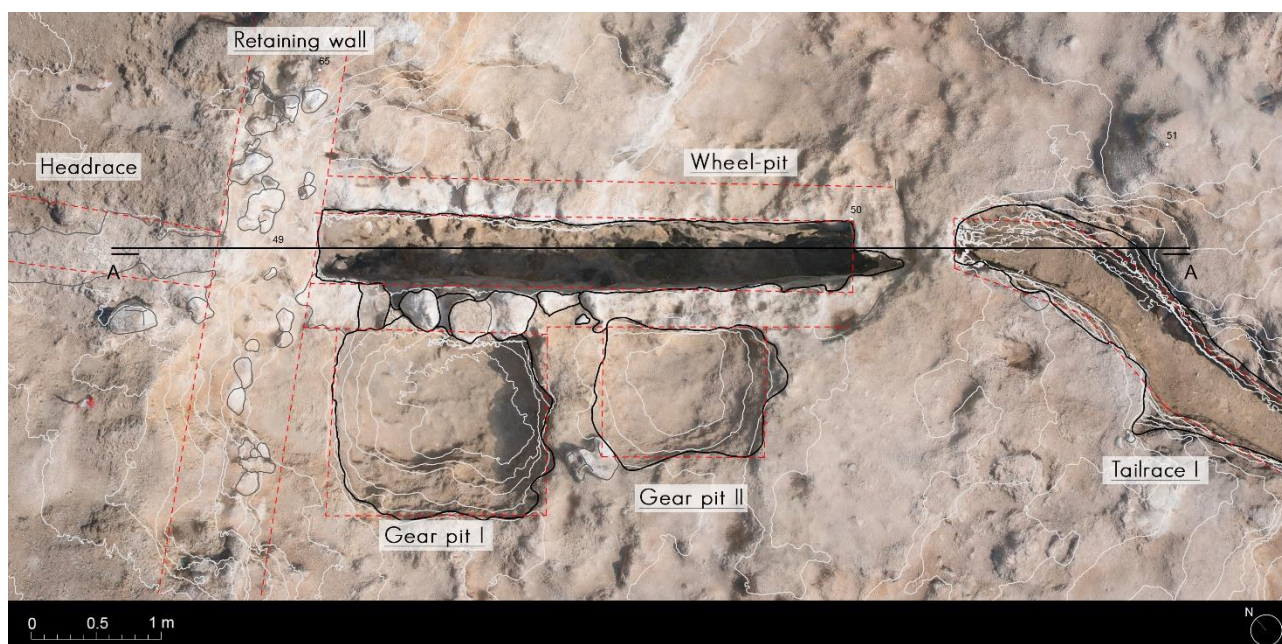


Figure 4: Ground plan drawing of the main elements of the waterwheel on an orthoimage generated through photogrammetry.

sea level, with an average flow that nowadays ranges from 350 to 500 l/s. The Roman channel reaches a height of 608.84 m at its final point, which implies a slope of 21.59 m in those 1.500 m. Thus, water ran down with a slope of 1.4% and flowed into a box containing the waterwheel. The force of water moved the blades. Then, water flowed through tailraces until reaching the main ditch.

Two areas with gear pits are annexed to the waterwheel, where the grain grinding machinery would be located. In the surrounding area, a building has been documented, which could be used by and related to the activity of the villa. Likewise, a necropolis of the late Roman period has been found (Fig. 3).

In the Roman channel, there is a retaining wall prior to a box containing a vertical waterwheel, whose rotation marks may be viewed on one of the vertical stone walls (Fig. 5). There is also an annexed compartment with two holes or pitches to fit the waterwheel gears and, in the surrounding area, millstones have been found. The complex also includes the tailrace for water and a large ditch to collect it.

So, the drawing of Figure 4 shows the following elements:

- The headrace that supplied water from the spring of *Las Fuentes del Marqués*.
- Retaining wall, perpendicular to the headrace.
- A box containing the waterwheel. Within this box, one of the vertical stone walls shows some marks forming part of a circumference (Fig. 5), which is the mark left by the waterwheel on the stone. The diameter of the waterwheel and its characteristics have been determined based on these marks.
- Annexed compartment with two holes or pitches to fit the waterwheel gears, according to Vitruvius.



Figure 5: Photograph showing the mark left by the waterwheel on the stone wall.

4. Methodology

For the accurate planimetric survey, we have combined different methods of graphic survey and measuring of historical structures, such as classical topography, 3D laser scanning and digital photogrammetry. In recent years, this complementarity of methods has proved to be the most accurate and efficient methodology for the documentation of the archaeological and architectural heritage (Remondino, 2011) and the most used methodology for the accurate graphic survey of heritage (Fassi, Achille & Fregonese, 2011; Yastikli, 2007).

The fieldwork started in February 2020, by measuring with the Leica Geosystems MS50 multi-station, which consists of a laser scanner and total station. Photogrammetric data were obtained with a Nikon D3300 camera, with a focal lens of 17 mm without a tripod (this allowed having more flexibility when gathering data). The intention was, as far as possible, that lighting was sufficient and that shadows did not impair the quality of work. A total number of 591 images of the complex were taken (Fig. 6).

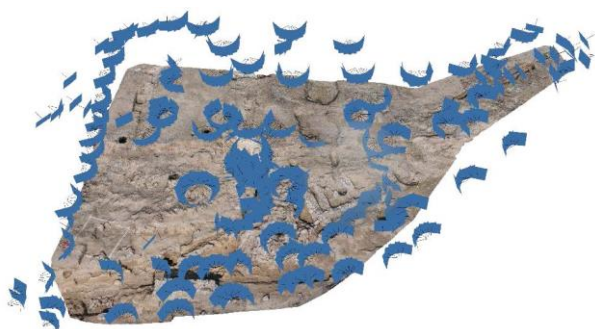


Figure 6: Relative orientation of the 591 images taken from the archaeological site *Hoya de Los Molinos*.

Photographs were taken in RAW format in order to subsequently carry out a colour correction with an X-Rite ColorChecker to obtain the optimal texture of the site. After having dumped the images, they were corrected and converted to .JPG format with Adobe Lightroom, in order to add them to the processing software.

The survey subject matter of this paper has been carried out by means of photogrammetric data supported by classical topography of the multi-station. Subsequently, images were oriented, by obtaining the calibration of the camera and the position of images at the time when they were taken with the Agisoft Metashape Professional v.1.7.1 software. These rings perfectly cover the whole area.

After having oriented the images, we obtain the 3D point cloud of the archaeological site. Based on this cloud, another cloud of higher density is obtained with 63 million points. Following the debugging and cleaning of the points from the external area to be modelled, the 3D model is generated by means of a mesh formed by the debugged point cloud. This point mesh is created in high quality in order to increase accuracy and to obtain the greatest number of sides, resulting in a model with 12 million sides. Once that the first 3D mesh has been obtained, the result will be exported to Geomagic Wrap v.2017. This software tool allows us to rebuild the mesh, repair any existing gaps and repair any incorrect sides. Once repaired, it will be exported to the modelling software Blender v.2.82, which allows us to sculpt the mesh in different areas in order to debug it, without modifying the 3D model geometry. After having completely debugged the mesh, the final texture will be applied, by correcting any defects and shadows of the texture with Adobe Photoshop v.2020.

The final result of the model is shown in Figure 7, with the textured model with the images taken and with a certain incline so that the various modelled structures may be observed.

Thanks to the 3D model of the site, obtained by means of digital photogrammetry, we can obtain the various planimetry and altimetry measurements of the archaeological site, including the most representative ground plans and sections, both in CAD format and as an orthoimage, which enables the subsequent analysis of the whole historical complex.

5. Discussion

It was decided to generate a 3D virtual digital reconstruction of the wheel, the gears and the space of the building that protected them to show how they would have been (Rodríguez-Miranda, Valle Melón, Korro Bañuelos, & Elorriaga Aguirre, 2021). After having analysed the characteristics of the water headrace and the box containing the waterwheel, we have determined the size and type of the original waterwheel, as shown in Figure 9. We have prepared a hypothetical reconstruction based on the research carried out by the archaeologists in charge of the excavation and the researcher Dr Robert Spain. As a reference, we have used the waterwheel of the Roman site of Hagendorn (Switzerland), which would correspond to the same period as that of Caravaca (Spain, 2008: 49). We have determined that the waterwheel radius was 1 m long, that the blades would be radial or quasi-radial (not buckets), that the water flow reached a medium height, the paddles would be flat and radial rather than inclined and that the waterwheel would rotate as shown in Figure 11. The paddles would not project beyond the shrouds (Fig. 9). From the end of the waterwheel to the base of the box, there is a 45 cm gap. The waterwheel box was rectangular: 4.13 m long, 0.55 m wide and 0.98 m deep. Water would fall down from 51 cm on the blades driving the waterwheel.

The reconstruction of the watermill gears and the rotation of the wheel until it drives the millstones have been determined according to the drawings made by Professor Dr Robert Spain, who visited the site and provided his valuable notes (Fig. 11). Figure 10 shows the dimensioned elements of the watermill gear machinery.

In the burial area, we can see the tombs of a necropolis of the late Roman period (Fig. 9). These tombs have been represented with an orthoimage, on which the outline of each of the eight tombs has been vectored. Subsequently, we have prepared one of the sections, crossing the tombs 1, 2 and 8, where their different depth may be noticed (Fig. 8).

We have also animated the various elements of the watermill. To that end, we have prepared the 3D model with Rhinoceros v.7 and, subsequently, each gear has been animated with the Bongo plugin.

This animation¹ starts from the rotation of the waterwheel on its main axis. This rotation is transferred to the first gear at the same speed. To that end, we replicate the animation of the waterwheel for the gear. Finally, the last element rotates on the X-axis, contrary to the previous pieces that rotated on the Z-axis and at a higher speed. That is why we apply the ratio between both gears when assigning the speed. The necessary supports have also been modelled to make it possible.

After having analysed the elements of the watermill, we have designed the hypothetical building protecting the gears. This building has been made light and transparent, to give an idea of the original volumes

¹ To see the result in motion, visit the following address for a video: https://youtu.be/D8rvQ36U_3s



Figure 7: Overall 3D photorealistic image of the archaeological site.

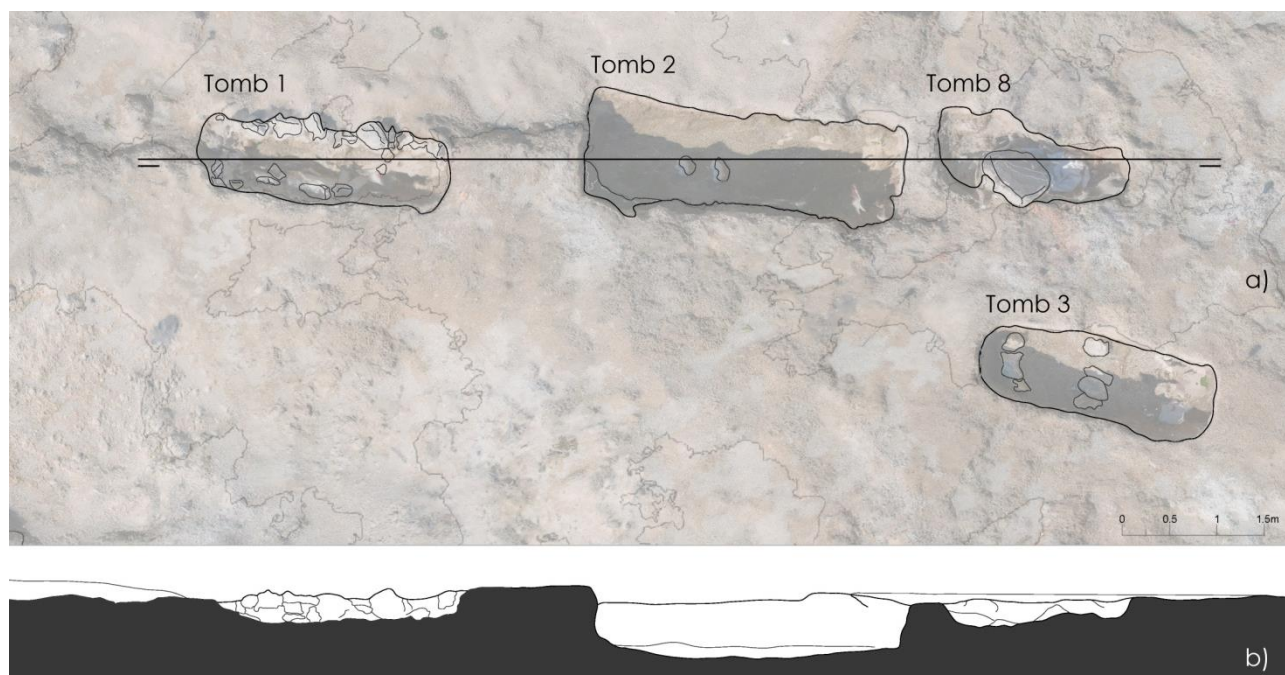


Figure 8: Necropolis of the late Roman period : a) ground plan; and b) section (tombs 1, 2 and 8).

(De Felice, 2016), but without deciding on the materials and construction techniques that were used in its construction, which archaeologists are still reflecting on. This is a two-storey building, with its roof sloped towards the waterwheel, in order to take advantage of rainwater as well. Covered gears would be located on the ground floor. And the millstones, hoppers and grain to be ground would be located on the upper floor (as seen in Figure 12). Access to the upper floor would be gained by using stairs, which would be located in the most elevated part, in this first hypothesis.

After having designed the hypothetical reconstruction, we have prepared the documentation for its subsequent

dissemination. To that end, various plans have been prepared to show the most significant areas, by emphasizing the area with the marks of the waterwheel and the various water channels. In order to support this documentation, an explanatory video has been prepared for the various areas within the 3D model by using the data obtained from the site and the scientific method followed by the hypothetical reconstruction of the wheel of the watermill, of all mechanical gears and the two-storey building. Both the video and the documents will be published, so that their information can be freely accessible. This will allow the public to know the site and to get quality measurements for their future research, where applicable.

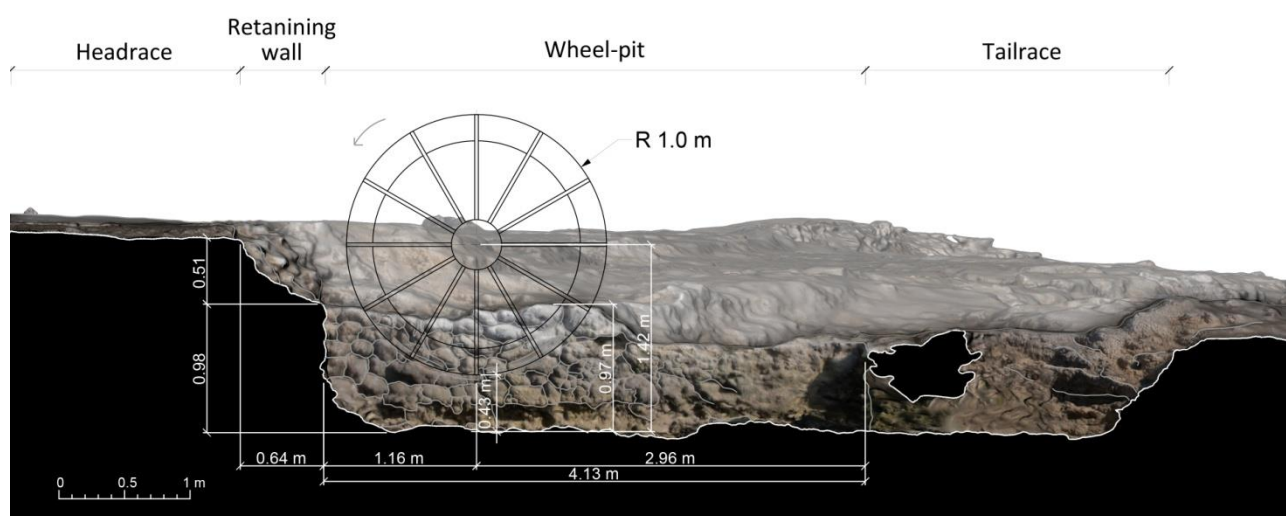


Figure 9: Reconstruction of the vertical wheel of the watermill, showing the dimensions and type of wheel, based on all the data gathered.

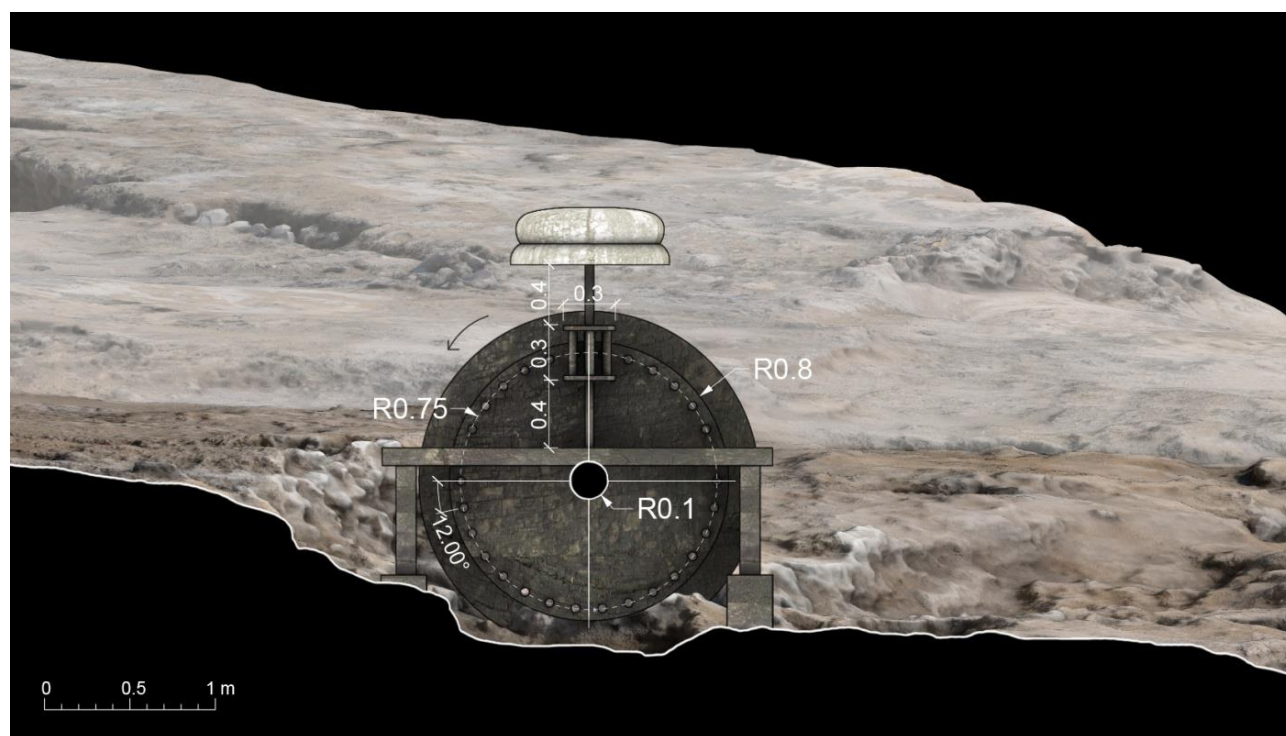


Figure 10: Section of the vertical-wheeled watermill gears, showing the dimensions, according to data provided by Robert Spain.

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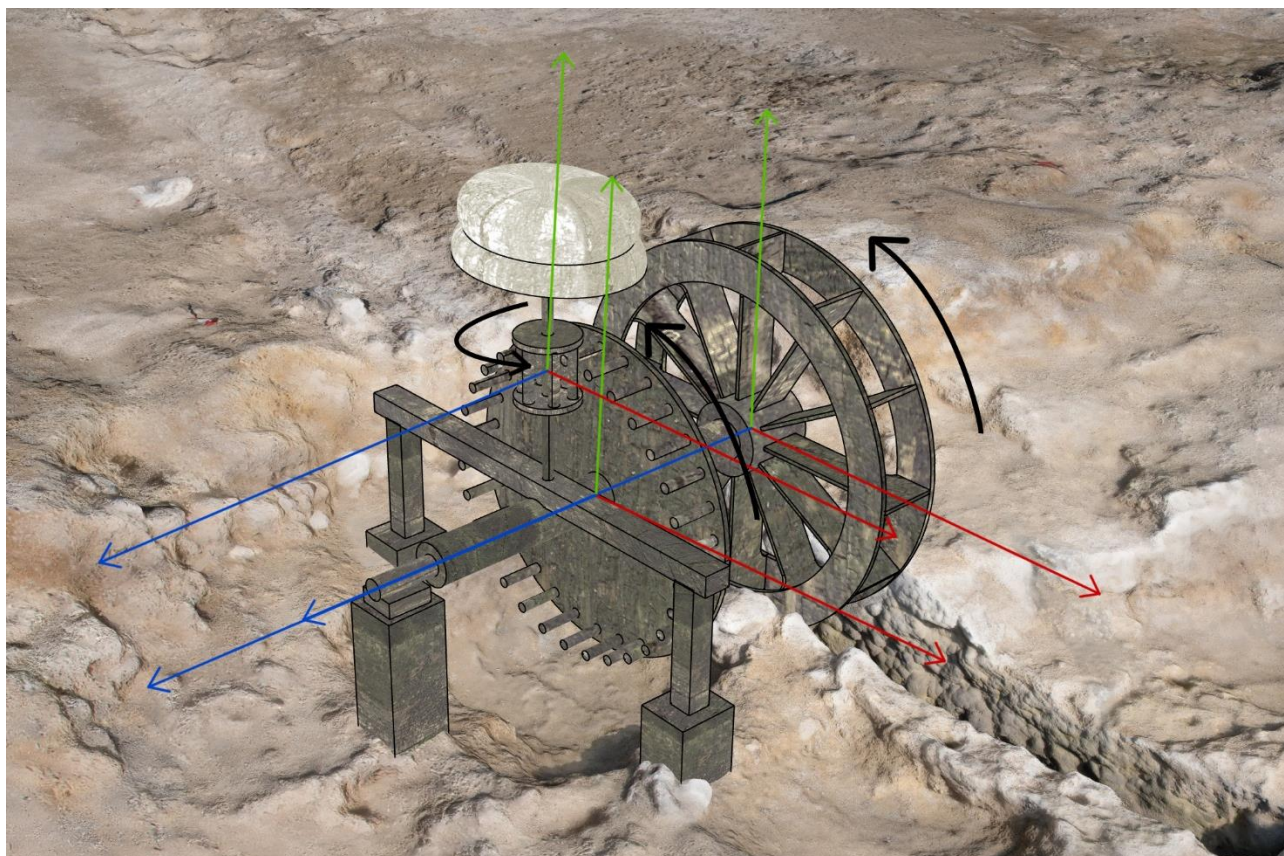


Figure 11: Reconstruction of the vertical-wheeled watermill gears, according to data provided by Robert Spain.

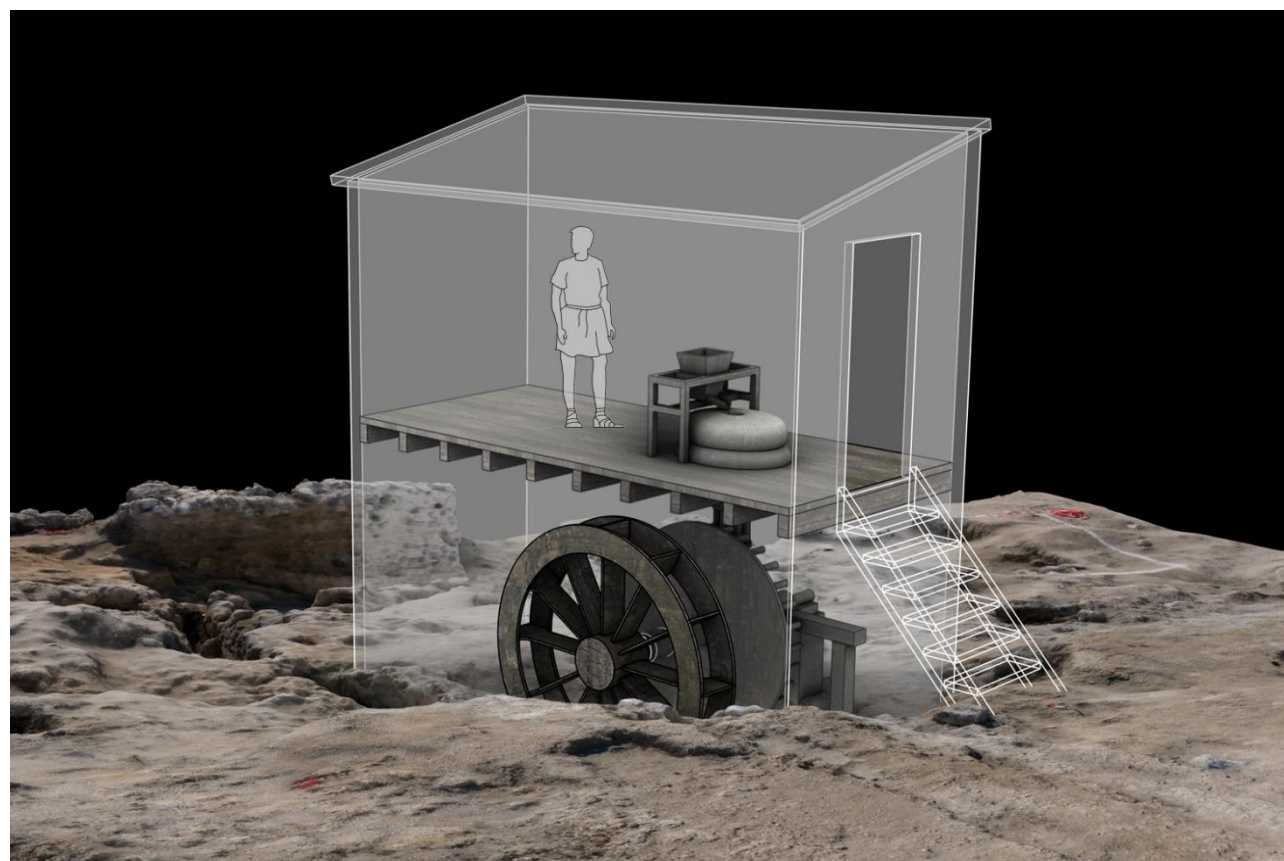


Figure 12: Hypothetical reconstruction of the building protecting the waterwheel gears and their supports.

Subsequently, we have 3D-printed the model of the whole site under study, as well as the detail of the waterwheel, with the hypothetical gears and building that housed and protected them. Printouts and the final video will be permanently exhibited at the Archaeological Museum of *Caravaca de la Cruz*. Videos contain music and descriptions of the elements and are easily accessible to any person interested in this matter. The intention is to guarantee their universal accessibility and to make all documents inclusive.

This graphic documentation is essential to future studies of the archaeological site, since it is currently beneath a new building. The hypotheses presented may be subject to modification as the research progresses; however, they are a useful tool to understand, enhance and disseminate the discoveries made in the archaeological site "*Hoya de los Molinos*".

6. Conclusions

Accurate documentation of an archaeological site has been carried out using complementary geomatic techniques before the archaeological site was buried. This documentation has been carried out by a multidisciplinary team. The archaeological site has been promoted by disseminating it through interactive material for inclusive museums, both the video and the different models made with 3D printers at different scales.

The information generated is publicly available but it would be very interesting to have institutional repositories and platforms specifically designed to host 3D digital heritage models and have these models in

them. That these sites can offer a range of useful functionalities (Champions & Rahaman, 2020; Naujokat, Glitsch, Martin, & Schlimme, 2020) to share data and results in the field of research, education, conservation or cultural tourism (García-Molina, González -Merino, Rodero-Pérez & Carrasco-Hurtado, 2021).

On the other hand, as future work, it would be interesting to make the temporal sequence of the site using the HBIM models (Santoni, Martín-Talaverano, Quattrini & Murillo-Fragero, 2021) in archaeology and virtual reality (VR) that are currently having a great development and progress thanks to the direct application of new grades of generation (GOG) and accuracy (GOA). It has been possible to explore the creation of informative 3D representations composed of sub-elements (granular HBIM objects) characterized by a higher level of knowledge (Banfi, 2020).

Finally, it should be noted that both the models and the video that have been made will be located in the Municipal Archaeological Museum of La Soledad, in Caravaca, for inclusive dissemination. With this, it is possible to contribute to the knowledge, musealization and dissemination of this important archaeological and cultural site finding in the Region of Murcia in Spain.

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