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Waiting for the rains: An attempt to evaluate the efficiency of the large Roman cistern at Barbariga Stancija (Casematte, Istria, Croatia)

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ABSTRACT: Access to freshwater has always been a critical factor in sustaining human settlements, especially in regions with limited water resources. In the Mediterranean region, where dry summers and karst landscapes limit water availability, ancient societies developed advanced methods for collecting and storing rainwater. Among these, cisterns played an important role in securing drinking water supplies. Despite their historical importance, the efficiency of these installations remains less studied than that of monumental aqueducts. This study focuses on a large Roman cistern at Barbariga Stancija in south-western Istria, Croatia, where rainwater harvesting was essential for sustaining local settlements and supporting intensive agricultural production. By integrating archaeological evidence, contemporary climatological analysis and paleoclimatic reconstructions, we have developed a quantitative model that simulates the performance of the cistern under varying rainfall conditions. The analysis uses high-resolution meteorological data and Weibull distribution-based simulations to estimate annual water storage capacity and variations in supply reliability. The study also assesses the maximum number of people the cistern could have supported, based on a reconstructed daily per capita water consumption rate. Our results suggest that under average rainfall conditions, the cistern could have reliably supported approximately 25–28 people throughout the year. However, seasonal variations in rainfall led to significant fluctuations in water availability, potentially leading to shortages during the dry summer months. Comparative analyses with other Roman cisterns in the Adriatic region provide a broader context for understanding the functionality and limitations of such storage systems within ancient water management strategies. This research not only enhances our understanding of local Roman hydraulic infrastructure but also contributes to broader discussions on sustainable water management in arid and semi-arid climates. It highlights the need for interdisciplinary approaches that integrate archaeology, climatology and hydrological modelling to comprehensively assess ancient water supply mechanisms and their implications for modern water conservation strategies.

KEYWORDS: ancient rainwater collection systems; Croatia; Istria; modelling of the efficiency of Roman cisterns; Roman cisterns

Introduction

Access to drinking water has become a global problem, exacerbated recently in Europe by major droughts with severe effects, especially in the Mediterranean region (Büntgen et al., 2021). Issues such as advancing climate change and growing world population will only increase the problem of water scarcity in the future (UNESCO, 2012; Collins et al., 2013). Therefore, understanding freshwater supply issues is extremely important. The Mediterranean region offers a unique opportunity to study past freshwater supply systems, thanks to numerous ancient remains of aqueducts, cisterns, wells, springs, fountains or underground sewage networks (Wikander, 2000; Klingborg and Finné, 2018). However, our understanding of water supply in the ancient Mediterranean is incomplete, as most studies have mainly focused on monumental infrastructure, especially aqueducts (Klingborg, 2017, 2023; Hodge, 2000; Klingborg and Finné, 2018), and less on cisterns or wells (e.g., Devoti, 1978; Thomas and Wilson, 1994; Klingborg 2017; Ward et al., 2017a, 2017b; del Mar Castro García, 2024). This emphasis has been increasingly criticized in recent scholarship (Klingborg, 2017, 2023; Klingborg and Finné, 2018; Glennie, 2023; Locicero, 2023), which highlights the need to pay greater attention to small-scale systems such as cisterns and wells) Reliance on cisterns was even more pronounced in parts of the empire where the local geology and hydrology made water supply systems, such as aqueducts and wells, less dependable and practical. One such region was modern Istria in Croatia, where there are only a few Roman aqueducts, barely some hundred metres long (Pola, Valbandon, Pomer: see Matijašić, 2018; for Verige see Gnirs, 1908).

From the Augustan period, most of the Istrian peninsula west of the Raša River was incorporated into *Regio X Venetia et Histria*, the tenth region of Italy, with slightly modified boundaries in late

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antiquity (Plin., Nat. Hist. 3, 44–5; Degrassi, 1954; Zaccaria, 1986). The karst landscape of the Istrian peninsula, especially in the south, influenced the need for sophisticated water supply systems, as this area, unlike many other karst regions, lacks reliable springs or other accessible water sources. The challenge was compounded by the dry summer months with little rainfall. Despite this, archaeological evidence shows a dense network of Roman settlements in south-western Istria, which was made possible by advanced rainwater harvesting techniques supporting both settlement and large-scale agriculture (Matijašić, 2018). Over 50 cisterns were documented, some belonging to large villa complexes or extensive centres of agricultural production, demonstrating the high efficiency of this method of collecting rainwater. Nevertheless, neither the cisterns themselves nor the question of their efficiency in this region have been researched in more detail (Matijašić, 2018).

This article aims to fill this gap by presenting a model that simulates the function of a large Roman cistern at the villa complex at Barbariga (Rice et al., 2024), analysing its role as a provider of fresh water for domestic use. This approach allows us to demonstrate how this installation operated, highlighting both monthly and annual, as well as year-to-year variations. By working with monthly data, we gain a deeper understanding of the dynamics of water supply and the variability of these resources on timescales critical to human survival. Our approach builds on previous studies of cistern capacity and seasonal supply (Connelly and Wilson, 2022; Klingborg and Finné, 2018; Glennie, 2023), which focus on small-capacity underground cisterns. As will be discussed in more detail below, the Barbariga cistern (so-called Central Cistern) is a large, seemingly free-standing cistern, the form and function of which varied from smaller rainwater collection systems.

First, an analysis of the structure and dimensions of the Central Cistern was carried out to understand the system of water collection. In the next stage, modern and paleoclimatological data from the Istrian region were compiled to reconstruct the possible rainfall structure for the Barbariga site. A determination of the amount of water that could be found in the cistern on an average annual basis followed. Lastly, an attempt is made to determine the maximum number of users that this cistern could regularly supply.

It should be clearly emphasised that the attempt to estimate the efficiency of the Barbariga Central Cistern is based on the currently available archaeological and paleoclimatic data, which are by nature fragmentary and cannot provide definitive answers to all the problematic questions. Due to the lack of an established and fully tested methodology for this type of analysis, this is a contribution towards its development.

In conclusion, the results of the presented simulations and modelling should be taken as approximate, as an attempt to answer the question of how effective Roman cisterns were in areas with permanent groundwater and surface water deficits, which undoubtedly includes the Western Istria region of present-day Croatia.

Geological, hydrological and geomorphological background

The archaeological site of Barbariga is in the south-western part of the Istrian peninsula, which occupies a geologically significant position within the Outer Dinarides (Fig. 1). This region is mainly composed of limestone from the Adriatic Carbonate Platform, formed during the Lower Jurassic to Eocene periods (Velić et al., 2002). The geological composition of the area includes carbonate deposits from the Middle Jurassic (Tišljar et al., 1998; Velić et al., 1995, 2003). More precisely, it is a thinly laminated Cretaceous limestone with deposits of calcareous breccia of Aptian age (Polšak, 1970). These deposits are covered by a thin layer of terra rossa, a soil formed mainly on carbonate rocks as a result of their weathering (Durn, 1996; Durn et al., 1999; Bašić, 2013). At Barbariga, the thickness of the terra rossa varies from a few centimeters to ca. 1 m, depending on local geomorphological conditions. Tectonic uplift on the Istrian peninsula has had a pronounced effect, with an estimated current vertical rate of about 0.75 mm per year. Studies of both geological and archaeological data suggest that sea level during the first and second centuries AD was probably 1.0 to 1.5 m lower than today (Faivre et al., 2010).

In the coastal area of Istria, most of the rainfall quickly infiltrates into the karst subsoil, contributing to the formation of a groundwater reservoir whose level fluctuates depending on the amount of precipitation (Polšak, 1970). This creates a fragile equilibrium between the infiltration of rainwater and the intrusion of saline water from the Adriatic Sea. The interaction between fresh and saline water sources is a critical aspect of water management in the region in view of freshwater resources preservation (Urumović et al., 1997; Rubinić et al., 1997). This process is exacerbated in areas where the water table is close to sea level, as is the case in Barbariga. During periods of low rainfall or drought, the lower water table infiltrates the aquifers, mixing with freshwater and increasing the overall salinity (Urumović et al., 1997). Over-exploitation of these aquifers, especially for agricultural and domestic purposes, further exacerbates the problem (Biondić, 2004).

Archaeological and architectural context

In the mid-20th century, excavations near the town of Barbariga revealed the remains of a large Roman olive oil production facility (Gnirs, 1901a, 1901b, 2009; Mlakar, 1956–1957; Marušić, 1975; Matijašić, 1982, 1988, 1993; De Franceschini, 1998; Bulić, 2014). The known remains cover an area of approximately 7500 m^2 and are located approximately 50 m from the seashore (Fig. 2) on a low-lying area that rises slightly towards the north, reaching 6 m above sea level at the rear of the site (Fig. 3). The architectural remains of the production facility cover an area of approximately 80 by 20 m and appear to be the northern wing of a larger complex, most probably related to a nearby maritime villa (Fig. 4) (Matijašić, 1982, 1988, 1993; Bulić, 2014; Bulić and Matijašić, 2022). According to available data, the Barbariga oilery was the largest of its kind in the European part of the Roman Empire. Roman olive presses that are similarly industrial in scale are mainly located in North Africa (Mattingly, 1988; Brun, 2004; Bowman and Wilson, 2013). Based on the preserved remains, the layout of at least nine olive presses was reconstructed (Matijašić, 1982, 1988, 1993; Rice et al., 2024). Obviously, the complex required an adequate amount of water both for the people and for the oil production process itself, which appears to have been supplied exclusively by rainwater collected and stored in underground cisterns, the remains of which have recently been discovered in the eastern part of the production complex. Since this area is still under study, details of its structure and functioning cannot be fully discussed at the moment.

Immediately to the east of the olive press facility, the remains of a large above-ground cistern (Central Cistern) are preserved, which probably supplied water to the domestic—representative part of the villa. The walls of the Central Cistern are preserved up to a height of about 3 m. There is no evidence to suggest that the cistern was originally higher than this preserved height; the robust *opus caementicium* construction of the northeastern, southeastern, and southwestern walls is maintained to an almost identical level, with the upper edges

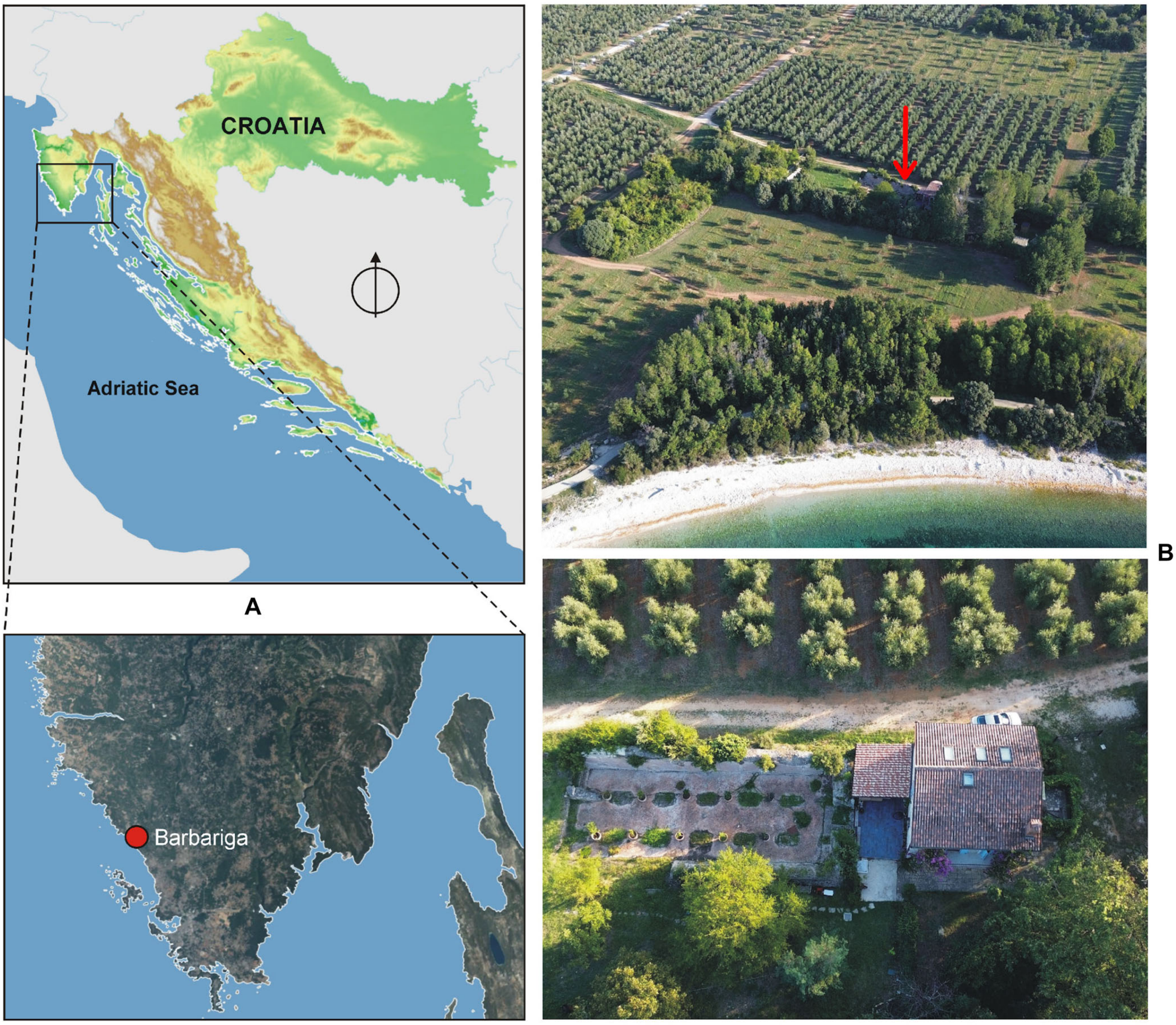

Figure 1. (A) Location of the Barbariga site. (B) Aerial photograph of the Barbariga archaeological site with the location of the cistern (red arrow) and an aerial view of its remains from the south (Drawings and photos: F. Welc). [Color figure can be viewed at wileyonlinelibrary.com]

forming an almost horizontal plane. Its internal dimensions are as follows: length: 21.70 m and width: 8.20 m (Fig. 5(A, B)). The northeastern and southeastern walls are 2 m thick. The floor of the tank consists of ceramic bricks laid in *opus spicatum* (Fig 5(C: 1)). The original presence of 10 pillars measuring 1.50 × 0.70 m (Fig. 5(C: 2)), arranged in two parallel rows, was established thanks to traces of these structures left within the *opus spicatum*. Along the SW, NW and SE walls of the cistern runs a low bench, c. 65 cm wide and c. 60 cm high (Figs. 5(C: 3) and 6: 4). A square niche is visible within it, which most plausibly indicates the location of one of the four outermost pillars (Figs. 5(C: 4) and 5: 5). A perfectly smoothed pink waterproof plaster, about 5 cm thick (Figs. 5(C: 5) and 7: 1, 2), has been preserved on the inner walls of the cistern (Fig. 7: 1). It has a visible admixture of finely crushed and sorted ceramics (Figs. 5(C: 5) and 7: 2–3). The corners were reinforced with an additional layer of this plaster to prevent leaks and cracks. In the lower central part of the southern wall of the cistern the main drainage hole (Figs. 5(C: 6) and 6: 7) with an external outlet and possibly the remains of a shut-off valve have been preserved (Figs. 5(C: 7) and 6: 8). The core of the cistern wall was constructed in *opus caementicum* (Figs. 5(C: 8) and 7: 2–3), a mixture of lime, sand and sharp-edged fragments of limestone up to several centimeters in diameter (Fig. 7: 3). This core was faced externally with a stone wall (Figs. 5(C: 9) and 7: 4) and was presumably supported internally with wooden scaffolding while it set and before it was faced with hydraulic plaster. An irregular opening in the SE wall (Figs. 5(C: 11) and 6: 1), a wall inside the tank (Figs. 5(C: 11) and 6: 1) and another opening in the southern wall are relics of later readaptations of the tank for other purposes (Fig. 7: 1).

A particularly interesting element of this cistern is its remarkably well-preserved drain, which allows the full reconstruction of its original appearance (Figs. 6: 7–8 and 8(A)). It consists of a block of quartzite (Fig. 8(C)), embedded in the structure of the cistern wall at the level of its floor. Along its longitudinal axis, there was a horizontal channel, 0.44 m high and about 0.20 m wide, which was widened several times so that the upper part of the block was destroyed (Fig. 8(C)). On the outside, the drain was formed by two overlapping stone blocks, of which only the lower one survived. A narrow drain channel had been carved along its longer axis, leading into a square cavity, which may have contained a shut-off valve (Fig. 8(C: 1)). It can be assumed that the original metal pipe, of which the valve was an integral part, was located inside the drain channel (e.g., Fassitelli, 1972; Hodge, 1992; Wiggers, 1996; Jansen, 2001, 2007; Ohlig, 2002; Wilson, 2006). The location of

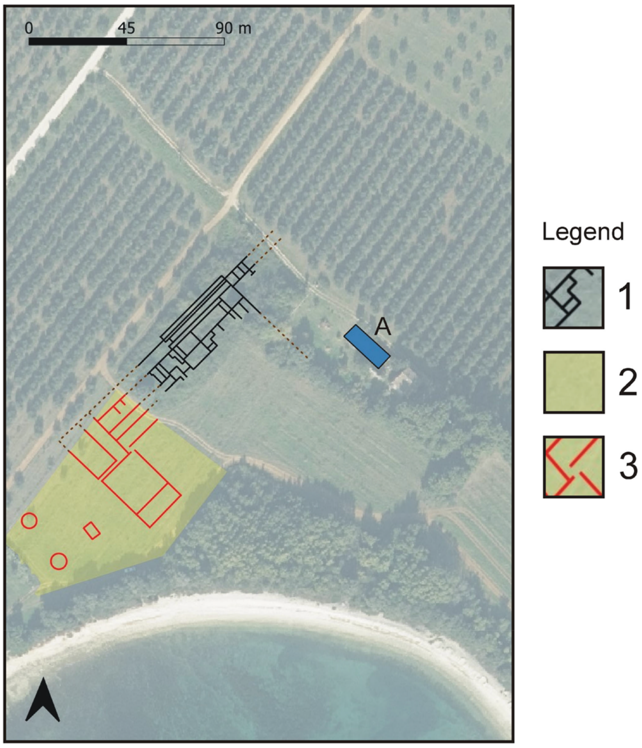

Figure 2. Barbariga archaeological site, (A) marks the location of the cistern. Legend—(1): Architectural structures discovered during the archaeological survey. (2): Area surveyed by geophysical methods in 2023. (3): The most important architectural structures located by geophysical profiling (Photo and drawing: F. Welc). [Color figure can be viewed at wileyonlinelibrary.com]

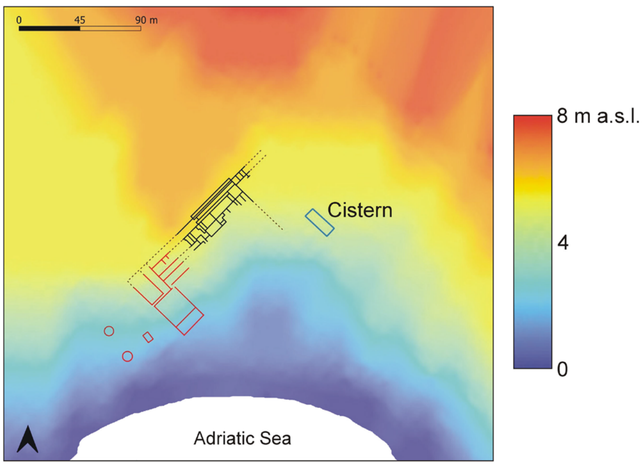

Figure 3. The Barbariga archaeological site with the location of structures exposed during excavations (black) and located thanks to geophysics (red) on the background of the altimetric map (Drawing: F. Welc). [Color figure can be viewed at wileyonlinelibrary.com]

the drain at ground level confirms that this cistern was an aboveground installation, the design of which had the significant advantage of not requiring water to be lifted out, but it could be controlled via a ground-level stopcock (Wilson, 2009).

The Central Cistern at Barbariga is structurally similar to other Roman water tanks built on the Istrian peninsula in the first centuries AD (e.g., Santa Marina cistern near *Parentium*, Rousse et al., 2014; cistern at Verige bay on the island of Brijuni, Gnirs, 1908, 1924; Begović and Schrunk, 2007; Bulić, 2014). Cisterns more than 2 m high were usually covered with barrel vaults supported by one or two rows of pillars (Matijašić, 2018). The Barbariga cistern had an analogous roof, as evidenced by the preserved remains of pillars dividing the interior into three chambers (Fig. 5). The above-ground cistern preserved in the bay of Verige contains four basins, three in a row and a large basin parallel to them (Gnirs, 1924) (Fig. 9(A–C)). On the northern walls of the tanks, there are two water outlets, one in each basin, located above the floor of the cistern, like at Barbariga (Fig. 9(C: 1–2)) (Gnirs, 1908, 1924; Matijašić, 1998). Similar freestanding cisterns are also known from Italy and were particularly common in southern Lazio (De Franceschini, 2005).

The absence of the roof makes it difficult to reconstruct the rainwater collection system in the case of the Barbariga cistern. Moreover, most Roman cisterns were sunk into the ground and were located either in the *atrium* or along one side of a central courtyard (for examples from Istria see Gnirs, 1924; Džin, 2006; Bulić, 2014; Matijašić, 1998; Starac, 2010; D'Inca et al., 2010; Bulić et al., in press). Pompeii is the best site for studying early Roman domestic rainwater collection systems. In many of its townhouses, water was collected from the sloping roof surfaces, that is, the effective roof area (ERA) (Butler and Davies, 2011). The water then flowed into the interior (*atrium*) of the building through the *compluvium*, an opening in the roof. Just below this, in the floor of the *atrium*, was the *impluvium*—a shallow basin that collected rainwater and drained it directly into an underground cistern (Adam, 1994; Sear, 2004; Jansen, 2023) (Fig. 10). Most *impluvia* had two or more drains. One of these drained to the cistern and the other (outflow) to the road when the cistern was full (Jansen, 2023). Directly under the thick layer of plaster, there was a channel that led the water into the cistern through a so-called inspection shaft (well). The latter allowed water to be drawn from the cistern.

Although the Pompeian houses provide detailed information on the structure of the rainwater harvesting system, they are not exact analogies to the cistern at Barbariga, which was built at ground level. To fulfil its function, it had to be of sufficient capacity and height. To supply it with water in the 'Pompeian' manner, it would have had to be surrounded by buildings of at least two storeys, with roofs of an appropriate shape (making the whole structure even higher). Although such a solution cannot be completely ruled out, it seems rather unlikely at the level of data we currently have. The survey carried out around the cistern in Barbariga did not reveal any substandard surrounding structures.

In addition, there is some possibility that water may have entered the cistern via an aqueduct. In a study of rural Roman cisterns in the Tiber Valley of central Italy, Wilson has argued that cisterns with capacities over 200 m^3 were too large to have been fed by rainfall collection alone, particularly when freestanding, and must have been fed by an aqueduct or small-scale conduit (Wilson, 2009). Aqueduct-fed cisterns are known from Croatia (Gnirs, 1908, 1912, 1924), but at present there is no evidence of an aqueduct at or even in the vicinity of Barbariga.

In view of the above, given the data we currently have at our disposal for modelling purposes, we propose here that the active surface (i.e., the water-absorbing surface) was limited to the roof of the cistern in Barbariga. Because the upper part of the cistern has not survived, we are unable to reconstruct in detail its water collection and drainage system. Based on the surviving systems in Pompeian houses, we can surmise that on the ceiling of the cistern at Barbariga, along its outer edge, there was a narrow channel covered with stone slabs (or ceramic tiles, as we have suggested here). The outlets of this channel were connected to an inspection shaft above its floor; this would have facilitated the deposition of any debris on its bottom, allowing clean water to flow into the cistern (Figs. 11 and 12). The large opening visible in the SE wall of the cistern could be a remnant of the overflow outlet, which was later widened when the cistern was adapted for other uses.

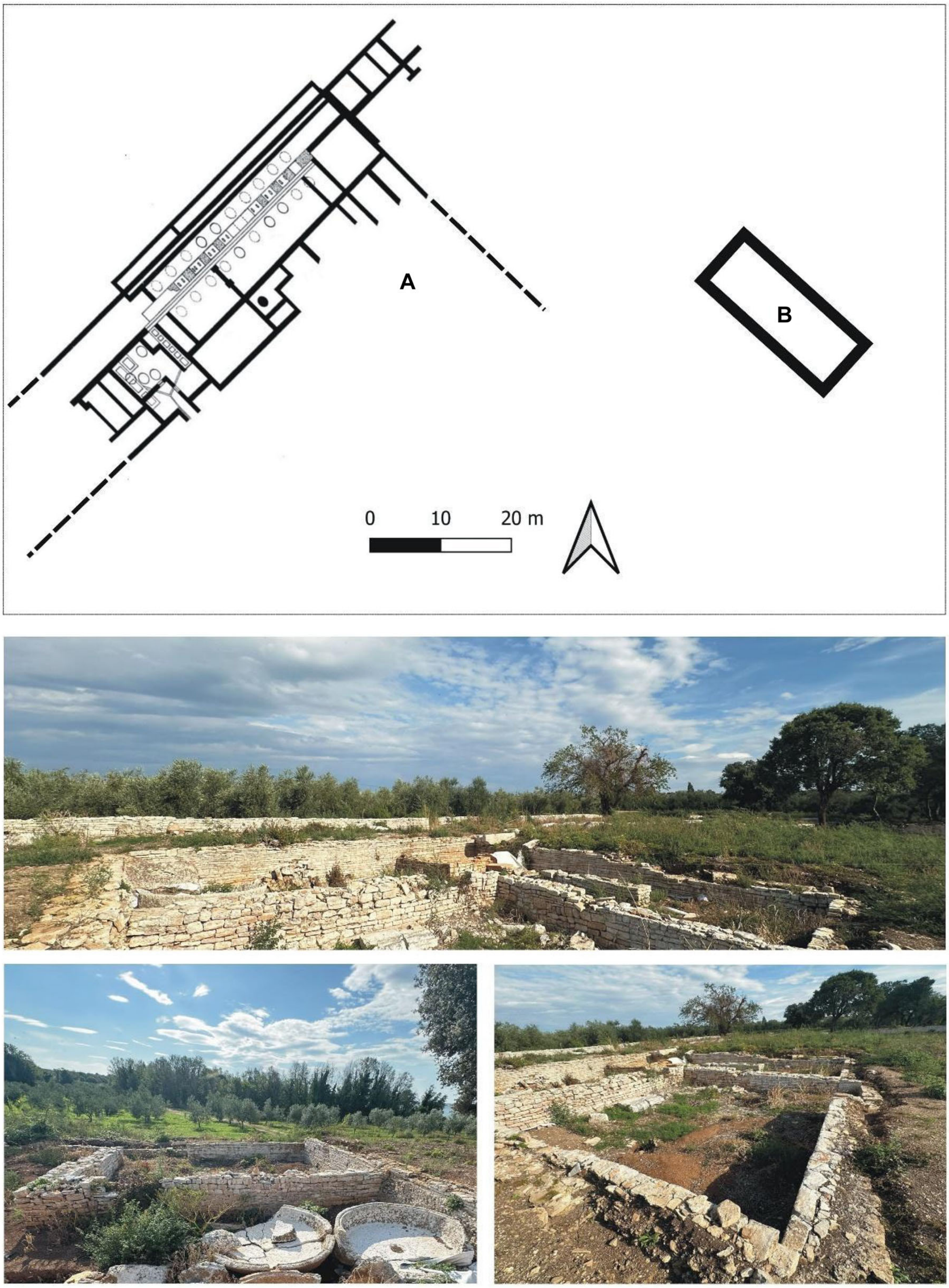

Figure 4. Above: Plan of the excavated part of the buildings of the Roman production complex at Barbariga (A) including the location of the cistern (B) (From: Matjašić, 1998, amended by F. Welc). Below: Photographs showing the present state of the uncovered architectural structures (Photo: F. Welc). [Color figure can be viewed at wileyonlinelibrary.com]

The fact that this opening is partially blocked by a low bench, which is a remnant of the cistern seal, suggests that the overflow outlet must have originally been above the bench and above the cistern floor. We can assume that the discharge of water from such a large cistern was controlled by a manually lowered sluice (Wilson, 2008; Schram, 2014). Considering the above observations, a probable reconstruction of the Central Cistern is proposed here, with its basic parameters such as size and capacity (Figs. 11 and 12).

Methodology for modelling the performance of the Central Cistern in Barbariga

The main objective of the modelling carried out was to estimate the average amount of water that could accumulate in the cistern each year and, in turn, to determine the maximum number of people it could sustain, in other words, to characterise the efficiency of the cistern storage system. The model assumed that the Central Cistern collected rainwater

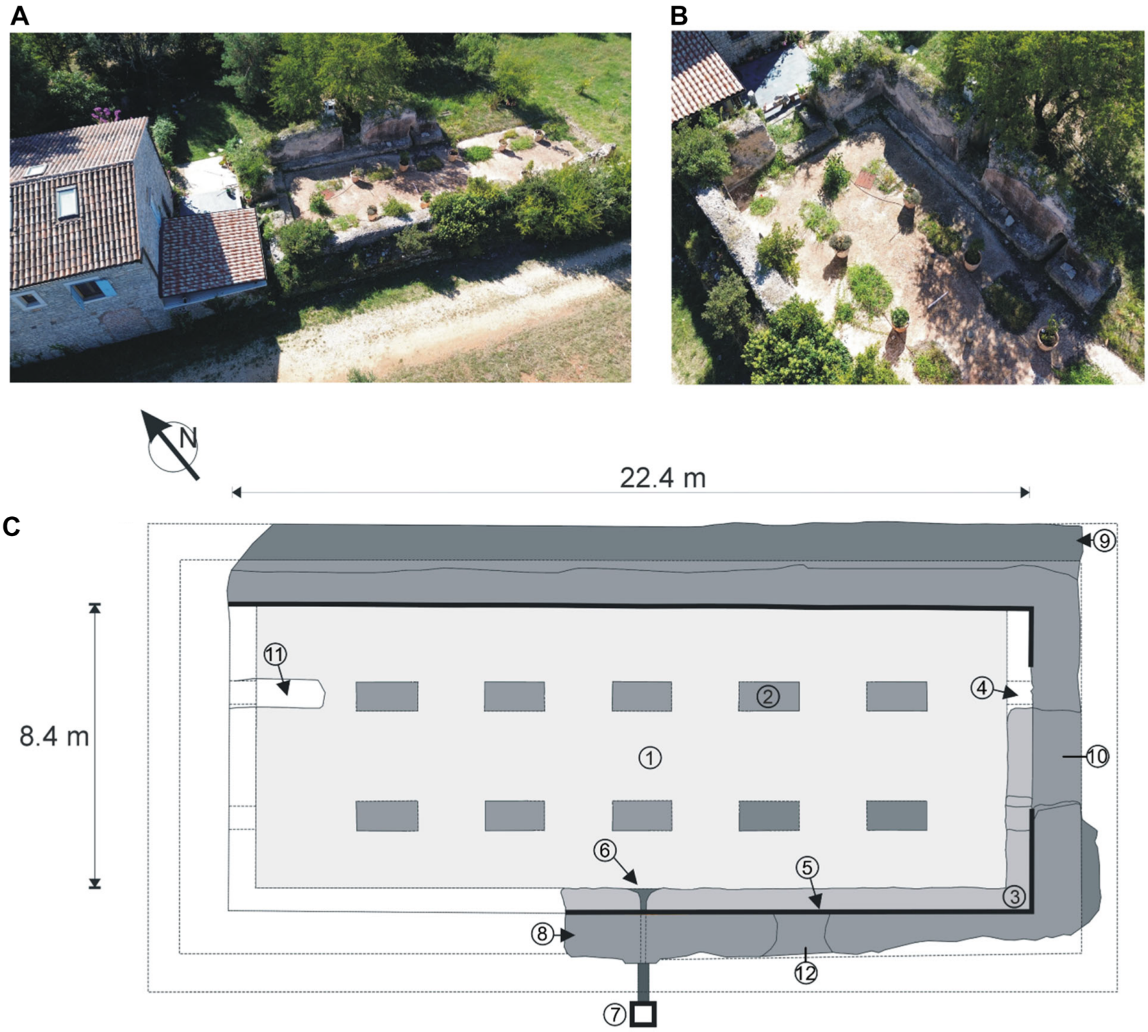

Figure 5. Preserved remains of the cistern in Barbariga. (A) View from the north-east. (B) View from the north (Photos: F. Welc). (C) Plan of the cistern remains at floor level. (1): *Opus spicatum* floor. (2): Remains of the pillars of the barrel vault. (3): Low bench—reinforcement of the connection between the walls and the tank floor. (4): Niches in the structure of the bench (remains of the internal pillars). (5): Layer of waterproof plaster preserved on the walls of the cistern. (6): Internal opening of the main outflow canal. (7): External part of the outflow channel end remains of a valve (?). (8): *Opus caementicium* core of the cistern walls. (9): External wall of the cistern. (10): A breach in the SE cistern wall, most likely a remnant of an overflow outlet, perhaps adapted later as an entrance opening. (11): A wall that is a relic of the adaptation of the cistern for other utility purposes. (12): A breach in the cistern wall, most likely serving as an entrance (a later adaptation) (Drawing and photo, F. Welc). [Color figure can be viewed at wileyonlinelibrary.com]

exclusively from the roof (see above) and that the stored volume was used by the inhabitants of the villa, that is, for domestic purposes. This last assumption is based on the results of recent archaeological work carried out at the olive mill at Barbariga (Rice et al., 2024) that uncovered the remains of at least one underground cistern, which could indicate that the production part of the Barbariga complex was supplied by an additional set of tanks, as the results of the modelling also seem to confirm.

To estimate the volume of water that could have accumulated in the cistern, it was necessary to know the distribution of rainfall during the period of operation of the villa at Barbariga in the first centuries AD. For this purpose, data were used from the Last Millennium Reanalysis (LMR) Project Global Climate Reconstructions Version 2 database, which covers the last 2000 years and contains information on rainfall anomalies compared to the climate values of the reference period 1951–1980 (Tardif et al., 2019). The temporal resolution of these data is 1 year, and the spatial resolution is 2×2 degrees. This information provided insight into the past climate picture, which formed the basis for further analysis. However, to get a more accurate picture of the distribution of precipitation, the next step was to use modern higher-resolution data. Thanks to this data, it was possible to carry out more detailed analyses, which allowed for a more accurate representation of precipitation variability in the region (Branković et al., 2013; Ivušić et al., 2024). Modern data served as a reference point for palaeoclimatic reconstructions, which is important for estimating the filling of the Central Cistern and understanding the climatic conditions during the period of interest.

In Croatia, average annual precipitation varies widely, from 300 mm to more than 3500 mm, with great variability over the year; these values are based on data collected from 1960 to 2020. The differences in precipitation over short distances are mainly due to factors such as proximity to the sea and the influence of the complex orography of the Dinaric Alps (Zaninović et al., 2008). Data from the climatological station in Rovinj (Sv. Ivan na Pučini, 8 m above sea level, 45°2′ N, 13°36′ E, about 14 km from Barbariga) provided by the Croatian Meteorological and Hydrological Service (DMHZ—Državni hidrometeorološki zavod) were used to determine the precipitation pattern in south-western Istria. The mean annual precipitation in Rovinj between 1981 and 2022 was 825.9 mm, with a standard deviation of 202.5 mm and a coefficient of variation (CV) of 0.25% (calculated as the ratio of the standard deviation to the mean precipitation, expressed as

Figure 6. Details of the remains of the Central Cistern in Barbariga: (1): Breaches in the S and SE cistern wall. (2): Internal opening of the main outflow canal. (3): Niche in the bench—remains of the pillar. (4): Low bench—reinforcement of the connection between the walls and the cistern floor. (5): Close-up of cistern floor. Remains of one of the pillars. (7): Close-up of the opening of the main outflow canal. (8): Close-up of the external part of the outflow channel with remains of a valve (?). (Photos: F. Welc). [Color figure can be viewed at wileyonlinelibrary.com]

a percentage). The highest precipitation was recorded from September to December, peaking in November (107.3 mm), and the lowest in July (42 mm), with the highest coefficient of variation at the same time. The high coefficient of variation (CV) in July (1.0) indicates a high variability of precipitation, with extreme differences between years (e.g., 184.6 mm in 2014 and 0 mm in several years). Autumn months such as September and October also show considerable variability in precipitation, which may be related to temporary weather conditions and the occurrence of intense storm events. The maximum and minimum data show that in some years there can be heavy rainfall (e.g., 356.9 mm in September 2017 or 221.4 mm in August 2002), indicating the possibility of extreme storm and flood events. In other years, there is almost no precipitation, for example, in December 2015, which can lead to seasonal water deficits (Fig. 13; Table 1).

The modern precipitation data served as input for the numerical model, which allowed the analysis of the variability of the water level in the Barbariga cistern, assuming that it was supplied entirely by atmospheric precipitation. The simulation determines the average water level in the cistern based on the Monte Carlo method, using the modern precipitation data measurements from the area of Rovinj presented above (Metropolis and Ulam, 1949; Kottegoda et al., 2014). The objective was to assess the volume of water resources under changing precipitation totals and to identify periods of water

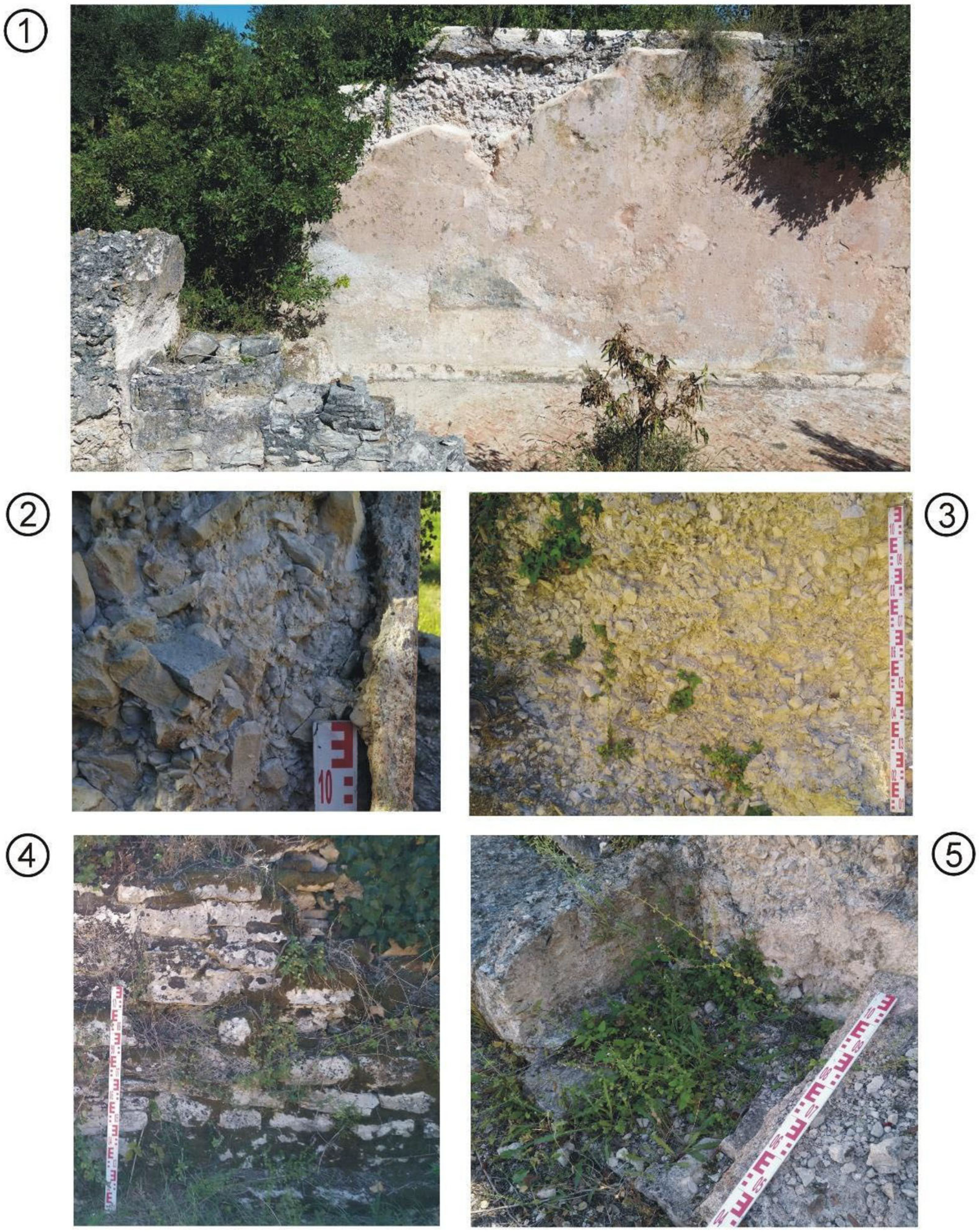

Figure 7. Details of the remains of the Central Cistern in Barbariga: (1): Layer of waterproof plaster preserved on the walls of the cistern. (2): Cross-section of the structure of waterproof plaster and core of the cistern wall. (3): *Opus caementicium*—core of the walls of the cistern. (4): External face of the northern wall of the cistern. (5): Close-up of the niche—remains of the internal pillar. (Photos: F. Welc). [Color figure can be viewed at wileyonlinelibrary.com]

deficit. This simulation also had to consider data uncertainty and the dynamics of hydrological processes (Ross and Marshak, 1991). Therefore, a Weibull distribution was used, which is often used in probabilistic analysis due to its flexibility and ability to model a variety of data types. The Weibull distribution has two basic parameters: the scale (λ), which determines the spread of the distribution, and the parameter (k), which determines the shape of the distribution.

$$f(x;\lambda,k)=\begin{cases}\dfrac{k}{\lambda}\left(\dfrac{x}{\lambda}\right)^{k-1}e^{-(x/\lambda)^k} & x\geq 0,\\ 0, & x<0.\end{cases} \tag{1}$$

A value of $\kappa > 1$ gives a right-skewed distribution (similar to the shape of a gamma distribution and has a decreasing hazard function, meaning that failures are more likely to occur early and then decrease over time) (has a decreasing hazard function, meaning that failures are more likely to occur early and then decrease over time), $\kappa = 1$ gives an exponential distribution, and $\kappa > 1$ gives a variety of asymmetric shapes, so it is able to reflect different shapes of the probability density function for the occurrence of given rainfall totals, which is particularly useful in the context of rainfall analysis where variability and unpredictability of the data are common challenges (Ross and Marshak, 1991). In other words, the Weibull distribution's flexibility allows it to adapt to different characteristics of the data, allowing for more accurate modelling and analysis of random variables with non-uniform distributions, such as rainfall, where both frequent low-intensity events and rare extreme values can be included in the analysis (Gąsiorowski and Szymkiewicz, 2016; Mikulski and Tomczewski, 2016). Assuming that the rainfall accumulation area is identical to the cistern bottom area, the current water level in the cistern is simulated based on the equation

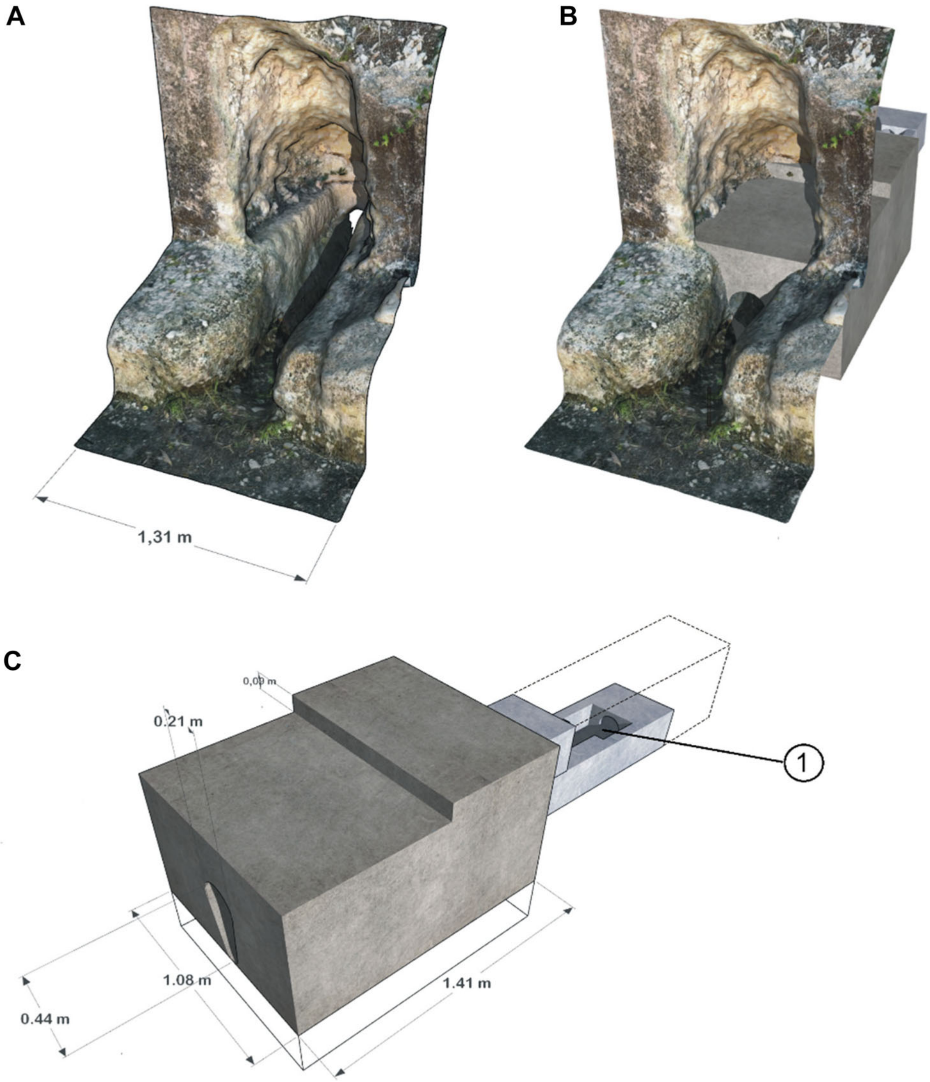

Figure 8. The preserved cistern drain channel—present state (A). (B) Reconstruction of the drain in the context of the surviving remains of the cistern wall. (C) Reconstruction of the drain with dimensions and marked the location (1) where the water shut-off valve may have been located (Photo and drawings: F. Welc). [Color figure can be viewed at wileyonlinelibrary.com]

$$H(t) = H(t-1) + P(t) - \frac{N^* \frac{C}{1000}}{A} - E(t) \qquad (2)$$

Where: $H(t)$ and $H(t-1)$ are the water level in the reservoir for day t and the previous day ($t-1$), $P(t)$ is the daily rainfall for day t, N is the number of inhabitants, C is the average daily water consumption per inhabitant, A is the surface area of the reservoir, E is the evaporation for day t. The daily rainfall ($P(t)$) is simulated based on the Monte Carlo model (random number generator) with a Weibull distribution and distribution parameters determined from climate data (Fig. 14). The model has been implemented in the MATLAB environment. In the first step, the monthly parameters of the Weibull distribution are determined based on data from the Rovinj station, covering daily rainfall totals from 1981 to 2022. In the next step, the water level for the next day of the year was calculated based on the random number generator and Equation 2. The annual parameter, which represents the variability of precipitation intensity, was 0.72 for Rovinj (Table 2).

Put simply, this model enables us to simulate how the water level in the cistern would change day by day based on estimated rainfall, water usage and evaporation. By repeatedly running these calculations with slightly different randomised rainfall patterns within realistic ranges, we can explore how the system might have behaved under different historical weather variability.

On the other hand, the different values of the scale parameter in individual months show the variation of rainfall intensity throughout the year. The highest scale values occur in the winter months (January, February, March), indicating a higher average amount of precipitation. In summer, the values of λ decrease (e.g., 0.65 in July), which may indicate a lower rainfall intensity in these months. The values of the shape parameter (κ) are higher in the autumn and winter months, for example, in September and October. Slightly higher values of k indicate greater regularity of precipitation, while slightly lower values indicate greater irregularity and periodic occurrence of extremes (droughts or very wet months).

Only rainfall exceeding 0.5 mm was considered in the Monte Carlo model, as lower rainfall values are unlikely to have a significant impact on tank supply due to evaporation effects in the open part of the tank (Vallet et al., 2016). The simulation included both the inflow of water into the tank due to rainfall and the outflow due to consumption by the villa's occupants. As the tank was closed and the only openings were water inlets with a maximum diameter of 50 cm, the effect of evaporation from the tank was eliminated. The maximum water level in the tank was limited by physical dimensions: it could not exceed the maximum height of the tank (approximately 2.5 m) or fall below zero.

To reduce the uncertainty due to the randomness of the rainfall generated and to estimate potential errors in the Monte Carlo model (e.g., errors in water level prediction), 100 parallel simulations were run over a period of 300 years. The results of the simulations show the percentage of days per year that the reservoir was empty at the assumed rate of use, as well

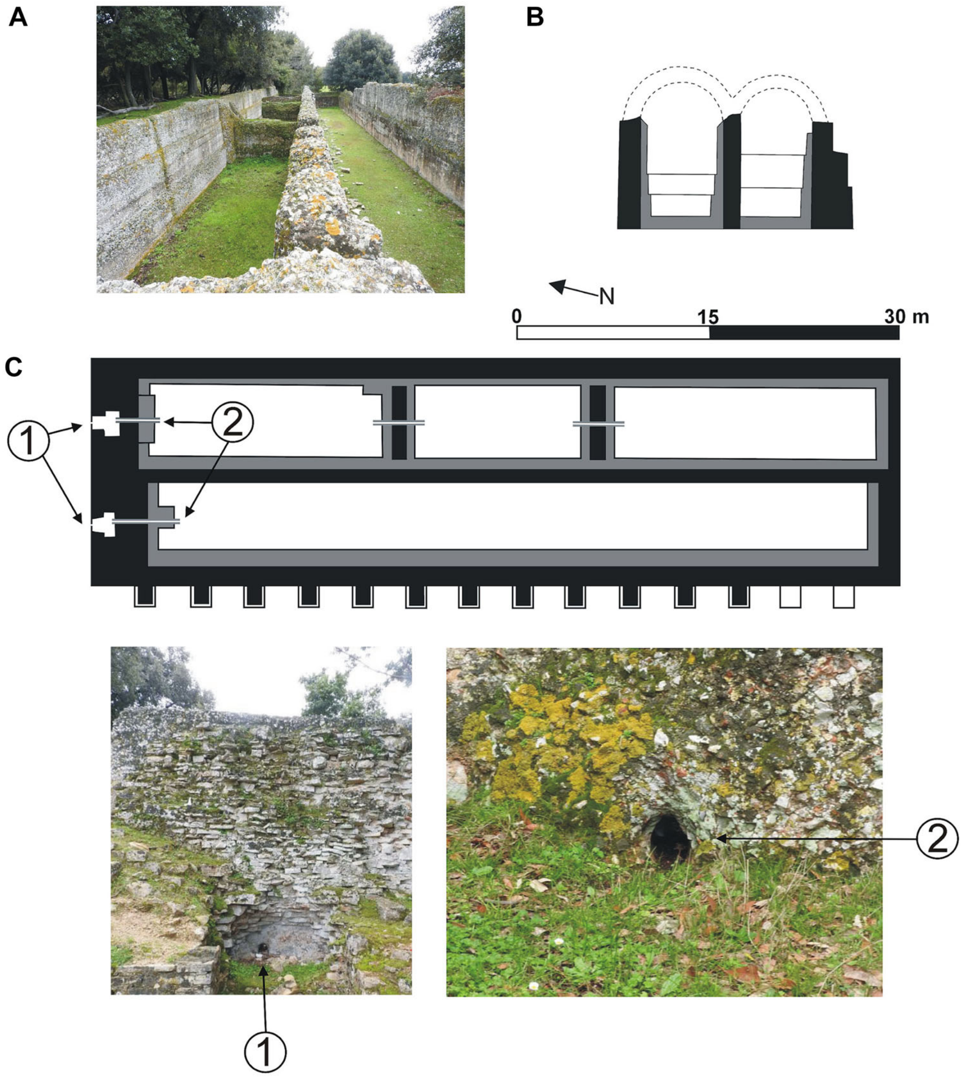

Figure 9. Remains of the cistern preserved in the bay of Verige, Brijuni Islands. (A) General view. (B) Cross-section. (C) Plan and photos of the cistern details—(1) remains of the external outlet, (2) close-up of the internal outlet (Photos: D. Bulić, drawings F. Welc, modified after Gnirs, 1924). [Color figure can be viewed at wileyonlinelibrary.com]

as the average water level in the reservoir and its standard deviation on individual days. It also shows long-term trends related to the seasonality of rainfall, which can be analysed by month or year. Thanks to this, the Monte Carlo model allows us to assess the capacity of the reservoir to meet the needs of the villa residents under different climatic conditions and population sizes, taking into account the natural variability of rainfall.

In order to model the capacity of the cistern to meet the water needs of the inhabitants of the villa, it was necessary to input the average consumption per person for the purposes of the model. This is not a straightforward number; even if we assume that the water is only being used for domestic consumption, there is almost no data on this for the ancient world. Some scholars have estimated that the average daily water consumption in the ancient city of Rome was as high as 67 L per person (Bono and Boni, 1996; Hansen, 2007). These estimates, however, include such things as the water consumed in the massive public baths and monumental fountains in an imperial capital where water was widely available thanks to numerous aqueducts. On the other hand, examples from 19th-century Europe show that in cities such as Paris or Liverpool, water consumption was between 14 and 16 L per person per day (Munir, 2010). A study of cisterns on the island of Geronisos estimated average consumption there at around 10 L per person per day (Connelly and Wilson, 2002). In addition to modest historical estimates, an important point of reference is the WHO guidelines, which define the minimum amount of water necessary for survival as 7.5 L per person per day, and the amount necessary for basic hygiene as 20 L per person per day (WHO, 2011). Considering the limited access to water in the Istrian region during the Roman period, it can be assumed that the actual water consumption was closer to these lower values.

Results

A comparison of the results from the LMR palaeoclimate database of precipitation for the first 100 years of the first millennium AD (probable period of the villa at Barbariga) with contemporary data (1900–2000 AD) showed that the average precipitation anomalies are similar in both such distant time intervals (Fig. 15). This analysis showed that the rainfall anomaly assumed for the ratio was only −2.7 mm for the 0–100 year AD period and −2.6 mm for the 1–300 year period (Table 3). It is worth noting that several palaeoclimatic reconstructions suggest the possibility of increased rainfall or generally wetter conditions during parts of the Roman period, although the picture remains complex and regionally variable (Büntgen et al., 2021; Jacobson et al., 2024; Finné and Labuhn, 2023).

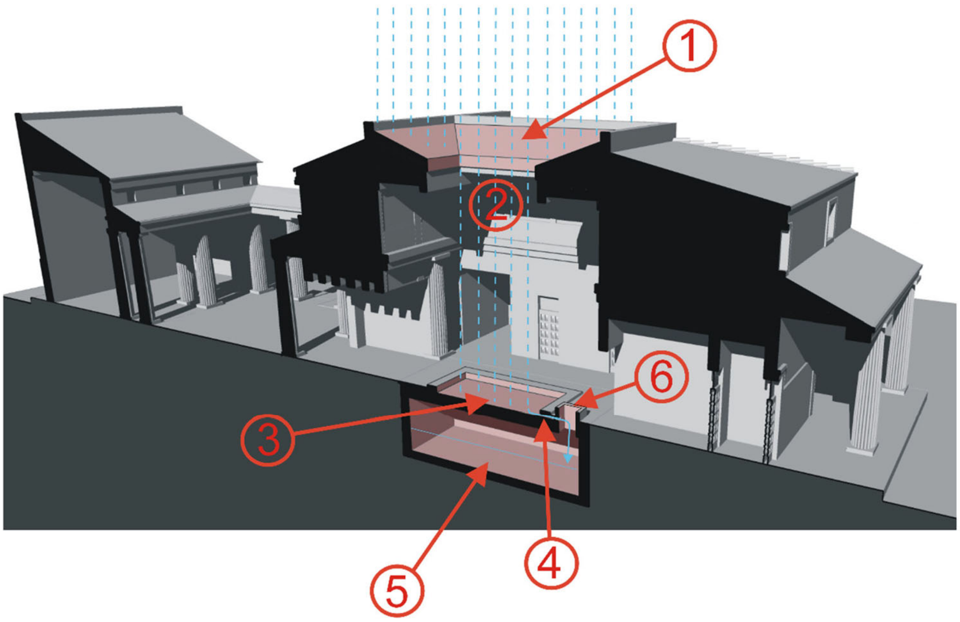

Figure 10. A cross-section of an idealised Pompeian town house. Rainwater was collected from the downward-sloping roof planes (so-called ERA: effective roof area) (1). Water then flowed into the interior of the building through an opening in the roof (2)—*compluvium*. Directly below, in the floor of the *atrium*, was the *impluvium* (3)—a shallow pool that collected rainwater running off the roof and delivered it through a drain (4) to an underground cistern (5). Access to the cistern was provided by a so-called inspection shaft (well), (6) which allowed it to be cleaned, repaired, and, above all, to draw water for domestic usage (Drawing: F. Welc). [Color figure can be viewed at wileyonlinelibrary.com]

These values are similar to those of the 20th century, when the precipitation anomaly was 15.1 mm. Taking into account the average annual rainfall in Rovinj of 825 mm, the difference in anomalies is 1.5%. Such marginal differences suggest that the average annual rainfall in the first centuries of our era was comparable to that of modern times. The Monte Carlo model was therefore based on contemporary rainfall data, allowing an accurate characterisation based on daily rainfall totals, from which monthly cycles were developed. This made it possible to reliably estimate the cistern's capacity under different climatic conditions.

The results of the simulations based on the data from Rovinj and consumption of 15 L per person show that water shortages occur in the cistern if more than 26 people use it daily (Fig. 16). Significant supply shortages, that is, more than 20% of empty days per year, occur at 34 people. The optimal number of users, at which water availability is guaranteed on most days of the year, is less than 25–28 people (Table 4). With a larger number of users, water shortages become the norm. For comparison, a simulation was also based on a water consumption of 5 L per day per person, in which case water shortages only start at 80 villa residents (Fig. 17).

An analysis of the average filling level of the cistern over the course of a year, with a consumption rate of 15 L per person per day, showed that for 25 cistern users, the average water level inside the cistern was 1.76 m, meaning that the cistern was almost full for most of the year (Table 5).

As a starting point, an initial water depth of 1 m was used. This assumption is only used to initialise the model. Due to the multi-century simulation span, this parameter has no significant impact on the resulting trends, which are determined by climatic input and usage dynamics.

However, if we assume that there were 30 users, the level of water stored in the tank drops sharply to just 0.22 m, which means that the tank was almost empty for most of the year (Fig. 18). The modelling results also showed that the seasonality of rainfall had a significant impact on the water level in the tank. The lowest level occurred in the summer months (May–August), when rainfall was at its lowest.

For 25 users, this level would not exceed 0.47 m, and for 30 people, only 0.18 m. In the fall (September–December), water levels increased due to more intense rainfall (Table 6). With 30 people, the level would be 1.20 m, which would significantly improve the availability of water (Fig. 19). In conclusion, the analysis of rainfall variability indicates that the Barbariga region is characterised by significant rainfall variability, but intense rainfall replenishes the reservoir water quickly enough that water shortages are rare.

Discussion

By attempting to model the water level in the cistern, it is possible to assess its ability to provide sufficient water under normal conditions and during droughts. By analysing the results, it is possible to determine how assumptions about the number of inhabitants and their daily water consumption affect historical accuracy.

For instance, if the model shows that the cistern was empty for a significant proportion of days (e.g., 30%–40%), this could imply that certain assumptions, such as those relating to rainfall, tank capacity or water usage, need to be revised. Alternatively, it could mean that the cistern's actual use or design in antiquity differed from what is assumed. These outcomes help to identify possible weaknesses in the model or our understanding of the cistern's function.

However, the question of what percentage of days the cistern could actually have been empty remains open. Such conclusions make it possible not only to examine the function of the cistern in the past, but also to formulate hypotheses about the daily life of its users.

The data suggests that it is realistic to assume that 25–30 people could have regularly used the cistern as their main water source, based on a consumption of 15 L of water per person per day. This number of users does not generate a surplus of water, which was the reality in ancient times. If consumption were reduced to 5 L per person per day, water shortages would only start to occur with around 80 inhabitants. However, this is a

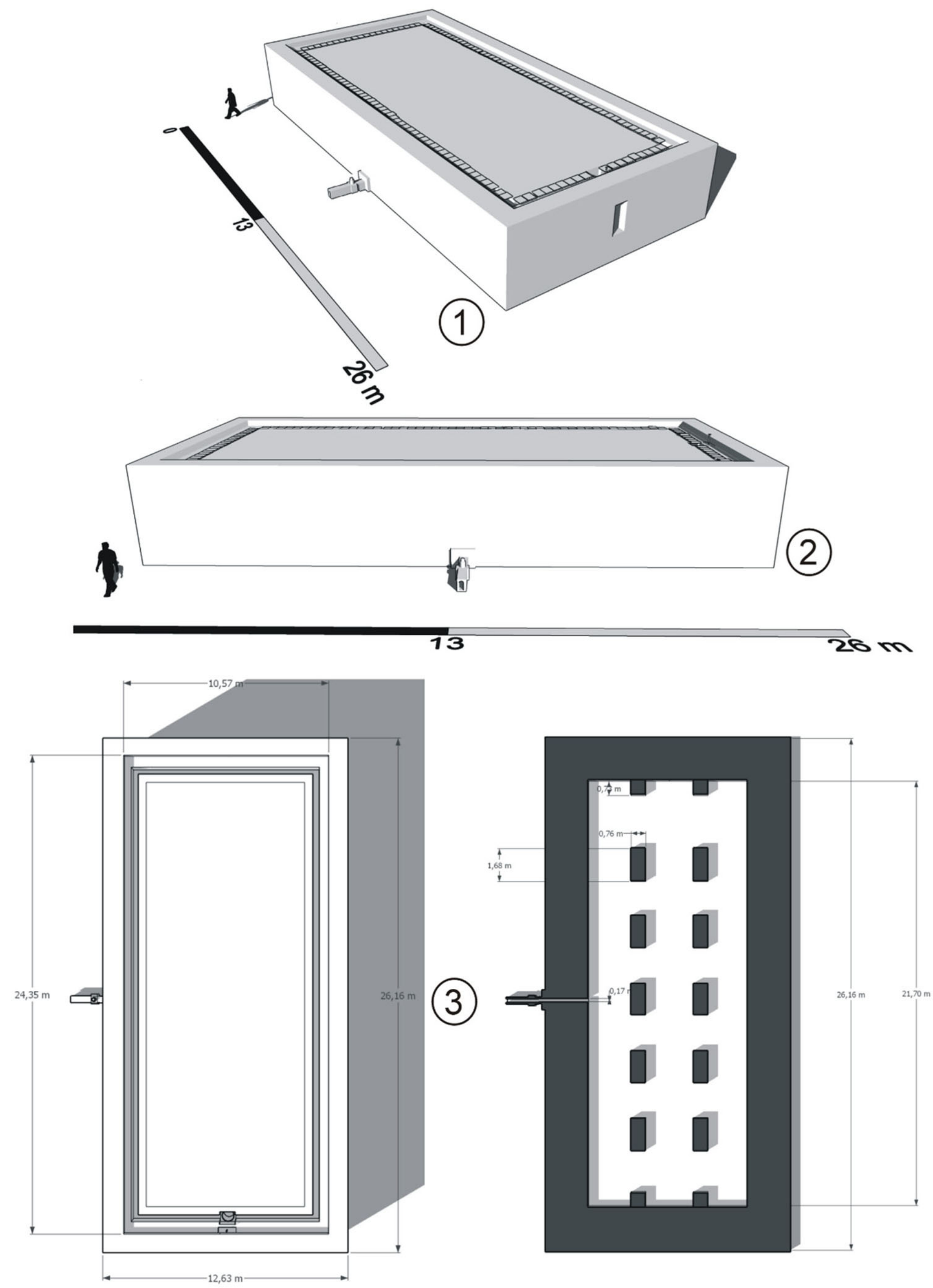

Figure 11. Spatial reconstruction of the Central cistern at Barbariga. (1): View from the south. Note the overflow channel. (2): View from the southwest. In the foreground, the main overflow channel with its hypothetical valve is visible. (3): Plan from above and horizontal cross-section with basic dimensions. (Drawing: F. Welc).

theoretical upper limit, as such low levels of consumption would probably only be adopted once water reserves had already begun to decline. However, this is too little to meet standard daily needs. In the Istria region, where water was a scarce commodity, it can be assumed that consumption was reduced to the absolute minimum of around 5 L per person during periods of drought. The results also show that seasonal variations in rainfall are crucial for water availability. At the same time, it should be reiterated here that a fragment of another large cistern, this time sunk into the ground, has been uncovered in the oil production complex nearby, which presumably provided the water necessary for the production cycle and other needs. This may suggest that the large above-ground cistern at Barbariga served as a main source of high-quality water for a relatively small circle of consumers—residents and workers associated with the olive oil production facility. This water may have been used mainly for consumption (including, for example, diluting wine or for cooking). Maintenance of the cistern roof, that is, the surface that collects water, was probably limited in scope. However, it enabled the collection of relatively uncontaminated water, unlike cisterns sunk into the ground, which collected runoff directly from roof slopes that were often polluted by animal faeces or overgrown with moss, especially on the northern side. A critical aspect of the Barbariga cistern is its structural design, which probably included a vaulted ceiling with integrated drainage channels, mirroring systems observed in Pompeian houses. The presence of a stone block outlet suggests that the water was actively managed, possibly through controlled release mechanisms. At this stage of research, we can only assume that the water from the cistern was channelled to the villa complex located closer to the sea through a system of lead pipes or water-resistant channels.

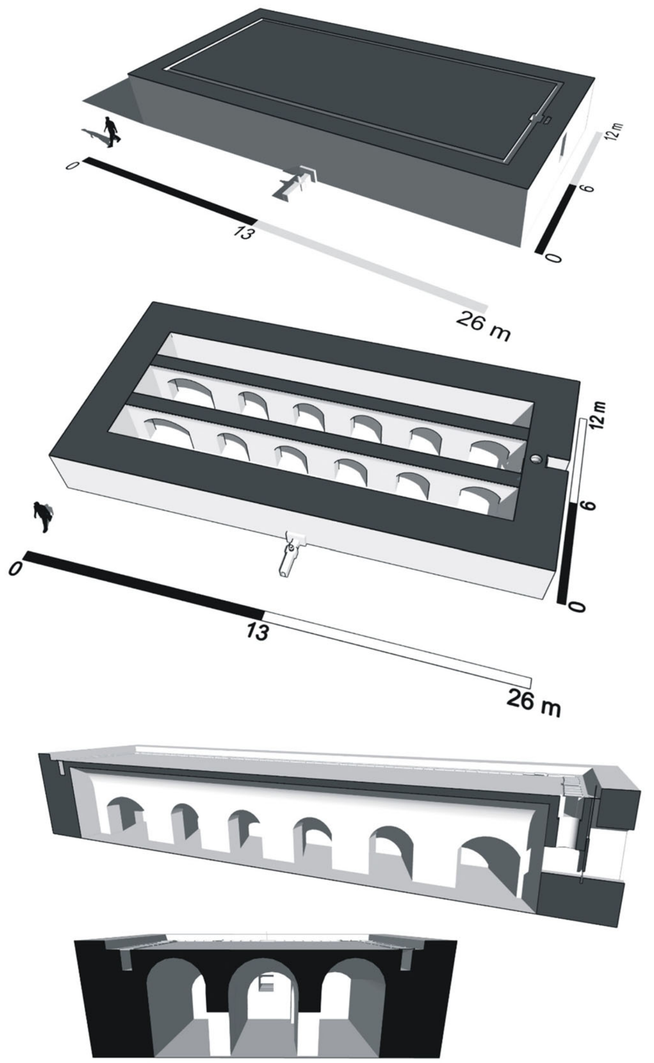

Figure 12. Spatial reconstruction of the cistern at Barbariga. Selected cross-sections and projections (Drawing: F. Welc).

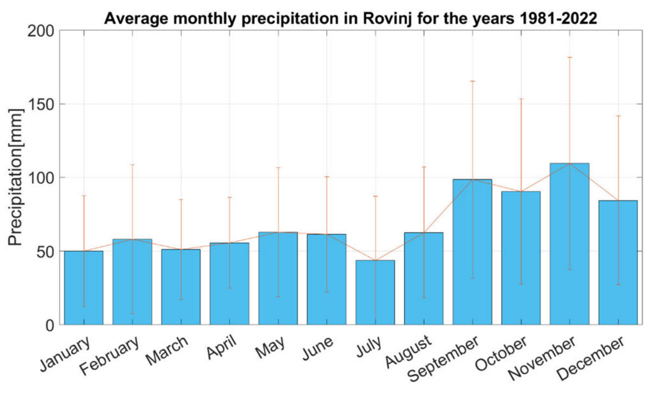

Figure 13. Long-term (1981–2022) monthly mean total precipitation observed at the Rovinj station. The blue bars show the precipitation totals, while the red bars show the standard deviation (Drawing: A. Han). [Color figure can be viewed at wileyonlinelibrary.com]

The analysis shows that the cistern, with its storage capacity, was able to supply water to a community of 25–30 people without frequent shortages. However, this balance was highly dependent on seasonal rainfall patterns. During the summer months (May–August), the water level dropped significantly, reaching critical lows when consumption exceeded supply. We can surmise that these periods of very low water levels were used for repairing and cleaning the reservoir. Conversely, the autumn and winter months brought sufficient rainfall to replenish the cistern and ensure stable water availability.

We will come to an interesting conclusion if, for example, we assume that the group of cistern users also included seasonal workers, essential for the oil production process. Because olive pressing in the Istrian area usually occurred in October, it was possible to begin harvesting already in the wetter month of September, engaging additional labour for that purpose. As a result, outside this period, the number of cistern users could be much lower, which would favour less water consumption and thus facilitate faster filling of the cistern tank. It should be emphasised once again that our calculations are based on the assumption that only the roof of the tank was an active surface. If the Barbariga cistern was surrounded by buildings with roof areas that acted as additional active surfaces, for example, with an area equal to the area of the cistern roof—i.e., 177.94 m^2—then the amount of water that would be flowing into the tank could be doubled, and so the number of people who could use it. As mentioned, there is no evidence at the site that the cistern was surrounded by buildings whose roofs could have been active water collection surfaces.

In addition, the model provides a comparative perspective on water consumption in antiquity. While estimates for ancient Rome suggest a daily per capita consumption of around 67 L, the figures for Istrian settlements are likely to have been significantly lower due to limited resources. The study supports the hypothesis that daily water consumption was around 10–15 L per person, which is in line with estimates from other Mediterranean settlements dependent on cisterns. This information is valuable for reconstructing population sizes and settlement organisation in regions where groundwater sources were scarce.

Another important finding is the resilience of the cistern system to interannual climate variability. Although periods of drought would have led to temporary shortages, the simulations indicate that the system was robust enough to maintain a stable water supply for most of the year. This strengthens the argument that Roman water management systems relied on a good understanding of climatic patterns and environmental constraints. The use of impermeable plaster linings, carefully designed drainage systems and the strategic placement of cisterns within settlements all contributed to the long-term effectiveness of these systems.

Finally, it should be noted that the research presented here is only one step forward on the issue of modelling the performance of Roman cisterns and, by design, it does not answer many questions or address many issues due to the limited amount of data at the disposal of the authors of the text. Further research should thus aim at understanding issues such as:

1. How frequent were periods of drought, and how did cistern users manage prolonged water shortages (e.g., through rationing, access to alternative sources or water reuse strategies)?
2. How often did cisterns overflow due to extreme rainfall events, and how was surplus water managed or redirected to prevent damage or waste?
3. What would water consumption have looked like if seasonal agricultural processing—particularly olive oil production—were taken into account?
4. Can models account for loss factors such as evaporation, leakage or siltation over time, and how do these affect long-term cistern efficiency?

Conclusion

The study of the Barbariga cistern represents a pioneering effort to determine the efficiency of Roman rainwater harvesting systems through quantitative modelling. The study confirms

Table 1. Long-term (1981–2022) statistics of monthly precipitation in Rovinj obtained from DMHZ.

Months	Average precipitation [mm]	Standard deviation	CV	Max Precp [mm] year	Min Precp [mm] year
January	50.0	37.0	0.74	127.5 (1984)	0.0 (1989)
February	58.0	49.9	0.86	194.3 (2014)	0.6 (1993)
March	51.1	33.6	0.66	138.0 (1995)	0.4 (2012)
April	55.7	30.4	0.55	124.3, (1998)	0.0. (2007)
May	62.8	43.2	0.69	218.1 (2010)	5.9 (2003)
June	62	38.5	0.62	160.3 (2008)	0.9 (2000)
July	42.0	42.8	1.02	184.6 (2014)	0.0. (2003)
August	64.2	44.5	0.69	221.4 (2002)	0.0 (2011)
September	97	66.0	0.68	356.9 (2017)	13.3(1983)
October	88.5	62.6	0.71	288.8 (1992)	10.9 (1988)
November	107.3	71.5	0.67	267.6 (1991)	8.1 (1983)
December	82.8	56.7	0.68	249.3 (2020)	0.0 (2015)
Sum	825.9	20.5	0.025	1422.8 (2010)	510.4 (1983)

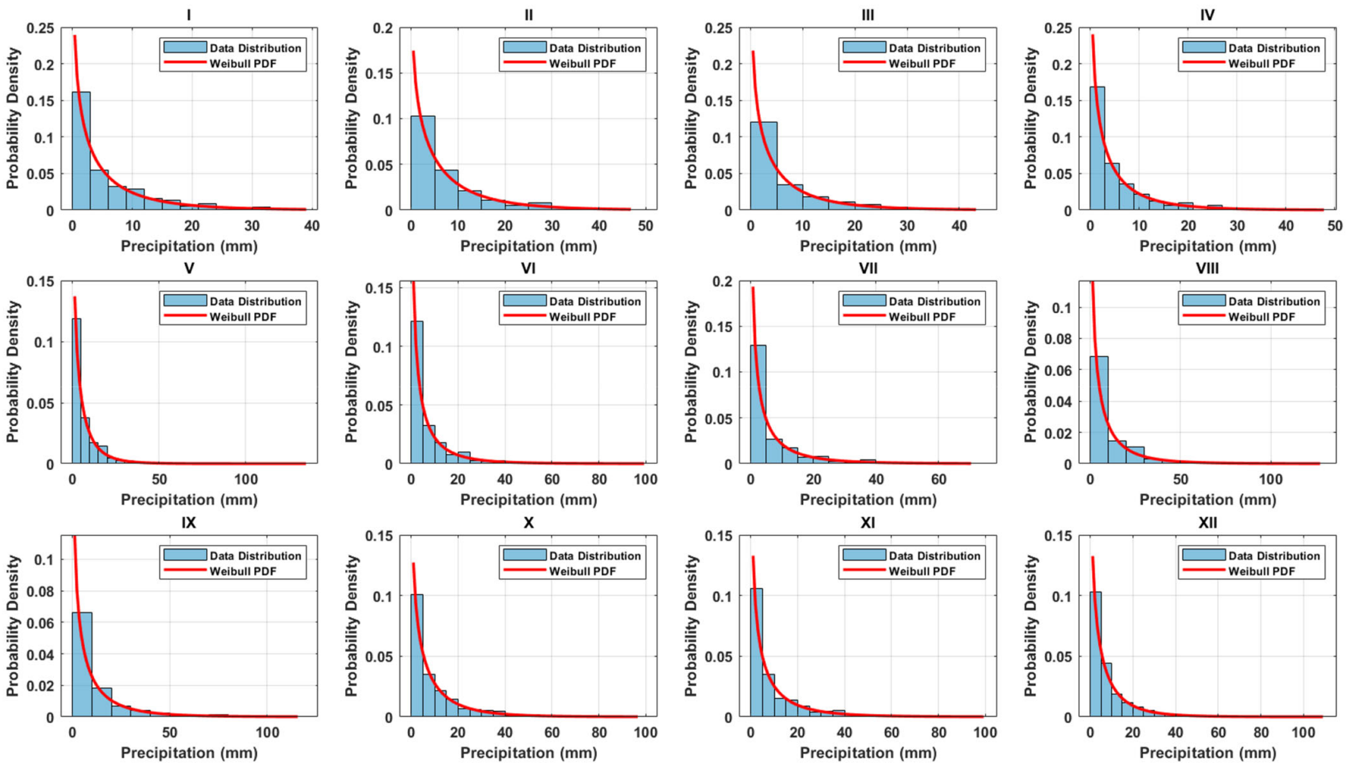

Figure 14. Probability distribution function of daily precipitation amounts, fitted to the Weibull distribution for the individual months. The histogram reflects the frequency distribution of precipitation, whereby the values are normalised to the probability density function (PDF). The red line is the fitted Weibull distribution curve (Drawing: A. Han). [Color figure can be viewed at wileyonlinelibrary.com]

Table 2. Parameters of the monthly Weibull distribution for Rovinj station.

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Scale	0.75	0.81	0.77	0.75	0.77	0.67	0.65	0.69	0.70	0.76	0.70	0.76
Shape	5.13	6.93	5.51	4.55	5.50	5.42	5.05	7.65	8.64	8.14	7.59	6.99

that this cistern could support a small population, probably made up of workers and residents associated with the olive oil production facility. By using both modern and historical climate data, the study bridges the gap between archaeological evidence and hydrological modelling, providing a replicable methodology for similar analyses in other Roman settlements.

One of the key contributions of this research is the demonstration of the ability of the cistern to regulate water supply over different seasons. The modelling results indicate that under average rainfall conditions, the cistern could meet the daily water needs of 25–30 people. However, during prolonged dry periods, this capacity was significantly reduced, necessitating strict water management practices. This supports the idea that Roman settlements in karst regions were highly dependent on rainwater storage systems, with little or no access to alternative freshwater sources.

The proposed methodology, combining palaeoclimatic reconstructions with Monte Carlo simulations to estimate historical

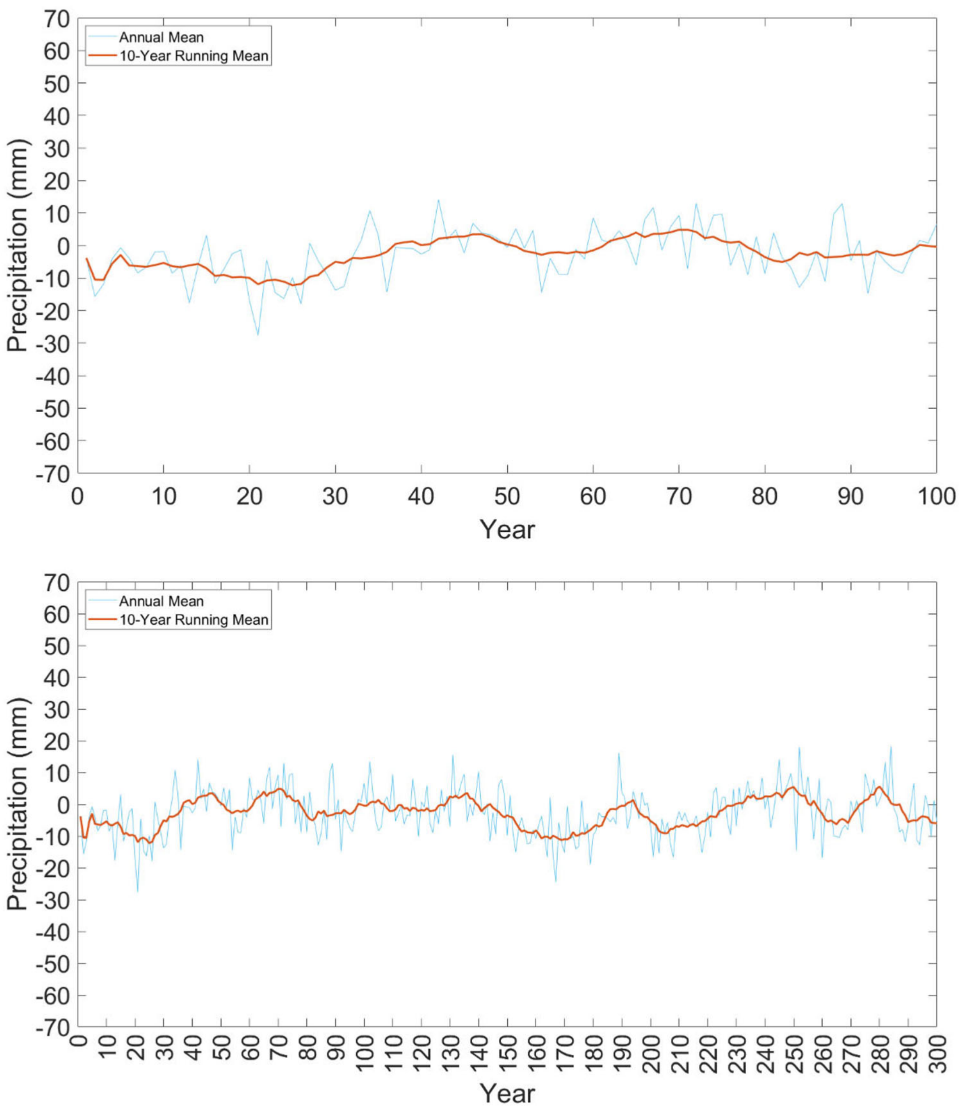

Figure 15. The graphs show the analysis of atmospheric precipitation in different time intervals, covering the periods of the last 100 years (up) and the first 300 years of AD (down). The paleoclimatic data comes from the Last Millennium Reanalysis (LMR) database and allows for a comparison of annual average precipitation totals, their variability and extreme values on different time scales. The blue line represents the annual average, while the red line represents the 10-year running average (Drawing: A. Han). [Color figure can be viewed at wileyonlinelibrary.com]

Table 3. Statistics of annual precipitation in [mm] obtained from the LMR database.

Year	0–100 AD	0–300 AD	0–1000 AD	0–2000 AD	1900–2000 AD
Mean	−2.7	−2.63	−3.5	−6.6	−15.1
Std	7.9	7.6	10.1	15.5	45.4
Max	14.1	18.2	33.1	57.8	92.9
Min	−27.6	−27.6	−45.8	−80.8	−127.1

water availability, provides a robust framework for assessing the sustainability of ancient water supply systems and can be applied to other archaeological sites with similar environmental constraints. The results also contribute to the wider discourse on climate adaptability in antiquity, demonstrating how past societies mitigated water scarcity through engineering ingenuity.

From a broader perspective, this research has significant potential for further applications in the study of Roman hydraulic infrastructure. By refining simulation techniques and incorporating additional archaeological data, future studies could extend this approach to larger villa complexes, urban centres and industrial sites. The results could also inform modern water management strategies, particularly in regions where rainwater harvesting remains a viable solution to contemporary water scarcity challenges.

Furthermore, this study highlights the need for interdisciplinary approaches to archaeological hydrology. By integrating climate science, hydrological modelling and archaeological evidence, a more comprehensive understanding of ancient water management practices can be achieved. Future research should focus on expanding the dataset to include additional Roman sites, allowing cross-regional comparisons and deeper insights into the role of cisterns in different environmental and socio-economic contexts.

In conclusion, the Barbariga cistern exemplifies the sophistication of Roman water management techniques, demonstrat-

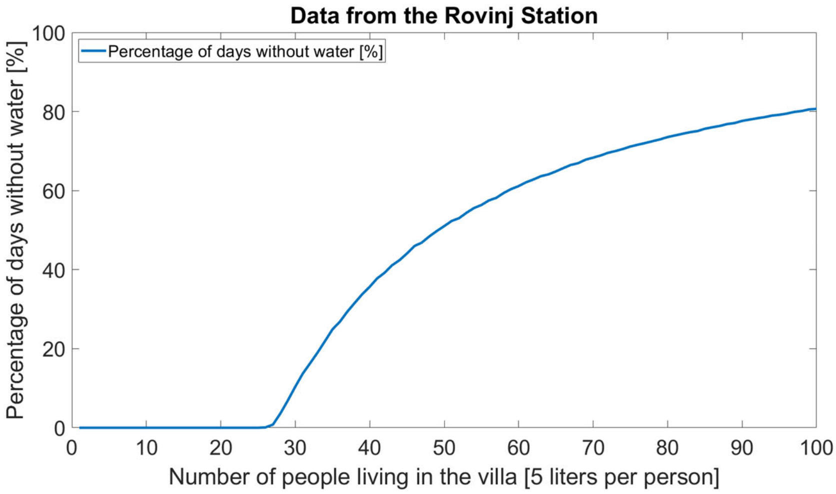

Figure 16. Percentage of days in a year when the cistern was empty, with a number of people using water at a consumption rate of 5 L per person, based on data from the Rovinj weather station (Drawing: A. Han). [Color figure can be viewed at wileyonlinelibrary.com]

Table 4. The percentage of days on which the cistern remains empty with a certain number of people living in the villa, assuming a consumption of 15 L per person per day.

Number of people	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
% of days the cistern was empty	0	0.08	0.69	2.91	6.6	10.21	13.01	16.53	19.38	22.15	24.88	27.22	29.32	31.56	33.53	35.50

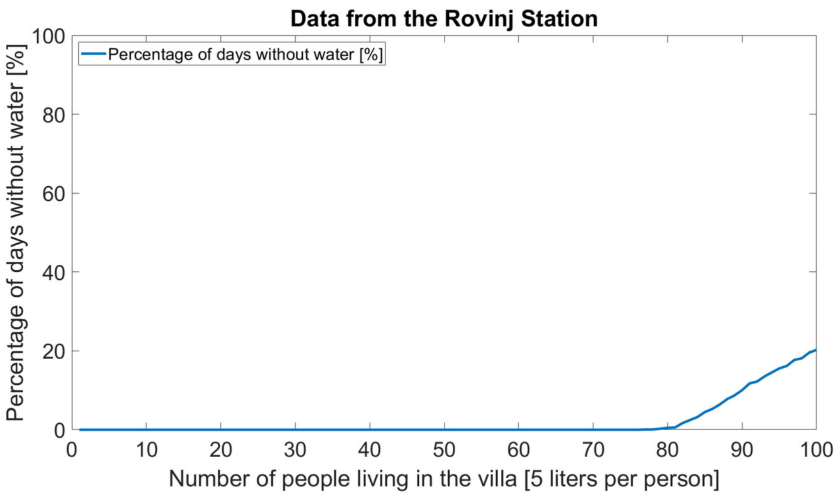

Figure 17. The percentage of days in a year when the cistern was empty as a function of the number of people using water at a consumption rate of 5 L per person, based on data from the meteorological station in Rovinj (Drawing: A. Han). [Color figure can be viewed at wileyonlinelibrary.com]

Table 5. Average cistern filling level throughout the year, based on 25 and 30 inhabitants, according to data from Rovinj.

	Mean [m]	Std [m]	Mean + std [m]	Mean – std [m]	Max [m]	Min [m]
25 people	1.76	0.25	2.10	0.93	2.29	0.9
30 people	0.22	0.09	0.27	0.01	1.00	0.04

Table 6. Rovinj—average water level in the cistern at a consumption of 15 L per capita per day.

Number of people	All year [m]	I–IV [m]	V–VIII [m]	IX–XII [m]
20	2.23	1.16	1.41	2.25
25	1.76	0.33	0.47	2.18
30	0.22	0.15	0.18	1.20
40	0.53	0.07	0.09	0.51
50	0.03	0.05	0.05	0.13

ing an adaptive and efficient system tailored to the specific hydrological conditions of the region. This study not only enhances our understanding of ancient water supply strategies, but also lays the groundwork for future interdisciplinary research in archaeology, climatology and hydrology.

The results suggest that the cistern was filled to a significant degree for most of the year, on average. While the exact manner in which the water was utilised cannot be inferred directly from this, the consistent availability of water implies that it was intended primarily for the personal needs of

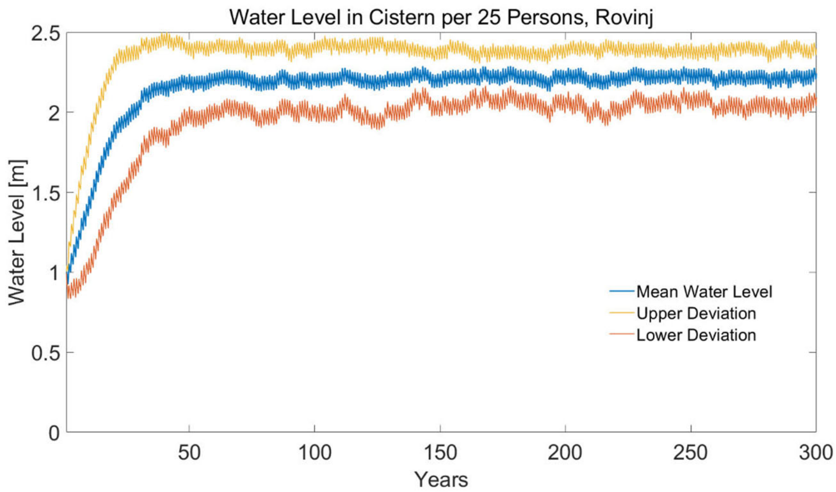

Figure 18. Average water level in the cistern with a 15 L per capita consumption per day, considering 25 people. The blue line is the average annual rainfall, the yellow line is the standard deviation above the mean, and the red line is the standard deviation below the mean (for the first 300 years AD) (Drawing: A. Han). [Color figure can be viewed at wileyonlinelibrary.com]

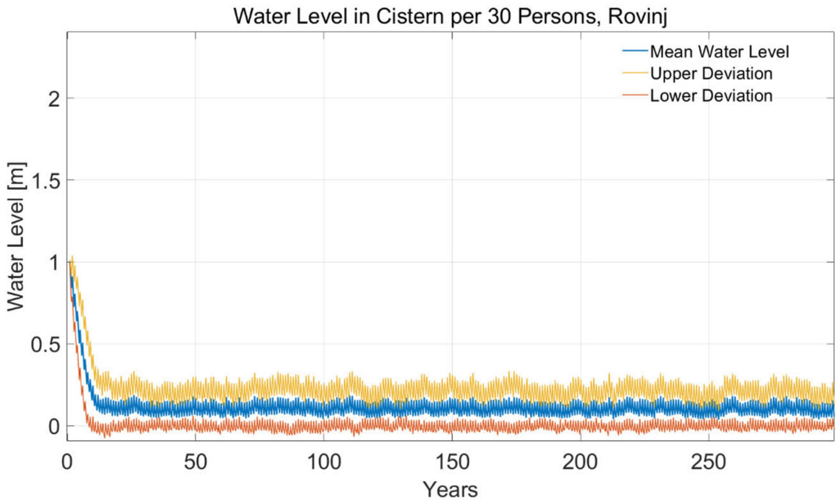

Figure 19. Average water level in the cistern with 15 L per capita consumption per day, considering 30 people. The blue line is the average annual precipitation, the yellow line is the standard deviation above the mean, and the red line is the standard deviation below the mean (for the first 300 years of AD) (Drawing: A. Han). [Color figure can be viewed at wileyonlinelibrary.com]

the inhabitants, particularly for drinking. Given its limited capacity and relatively stable fill level, it is unlikely that the cistern supplied water for other domestic uses, such as watering animals or doing household chores. These needs may have been met by alternative, lower-quality sources. This highlights the cistern's role as a reservoir of high-quality drinking water for the daily needs of household members.

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DATA AVAILABILITY STATEMENT

All data supporting the findings of this study are available from the corresponding author upon reasonable request.

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