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Modern Use of Traditional Rainwater Harvesting Practices: An Assessment of Cisterns' Water Supply Potential in West Mani, Greece

Theano Iliopoulou [1,*,†], Panayiotis Dimitriadis [1,†], Aimilia Siganou [2,†], David Markantonis [2,†], Konstantina Moraiti [2,†], Maria Nikolinakou [2,†], Ilias Taygetos Meletopoulos [3,†], Nikos Mamassis [1,†], Demetris Koutsoyiannis [1,†] and G.-Fivos Sargentis [1,†]

[1] Laboratory of Hydrology and Water Resources Development, School of Civil Engineering, National Technical University of Athens, Heroon Polytechneiou 9, 157 80 Zographou, Greece
[2] School of Civil Engineering, National Technical University of Athens, Heroon Polytechneiou 9, 157 80 Zographou, Greece
[3] School of Architecture, National Technical University of Athens, Heroon Polytechneiou 9, 157 80 Zographou, Greece
* Correspondence: tiliopoulou@hydro.ntua.gr
† The authors contributed equally to this work.

Abstract: Water has always been a driver of human civilization. The first human civilizations thrived in places with an abundance of water, typically nearby large rivers as the Tigris–Euphrates, Yang Che and Nile. The invention and construction of hydraulic infrastructure came only later, in prehistoric times, triggered by the expansion of humanity in water-scarce areas. The ancient Greeks invented impressive hydraulic works and small-scale structures, some of which, such as cisterns, were still fully operational until the 20th century. We present a model that explains the use of cisterns in the water-scarce area of West Mani, which allows us to assess the potential of this traditional rainfall harvesting practice to support the modern water supply needs. To assess the system's reliability, we employ a long-term simulation of a typical cistern system, using synthetic rainfall series from a stochastic model, and assuming variable water demand on a monthly scale. We show that a proper restoration of the cisterns could be sustainable as a complementary water supply source, decreasing the area's drinking water cost and increasing the locals' resilience against water shortages. In addition, we highlight the links between the area's hydroclimate and its history and discuss the cultural merits of reviving and preserving this centuries-long practice.

Keywords: water management; local-scale; cisterns; traditional water harvesting; rainwater harvesting; water-scarce areas; water-related heritage; cultural heritage

Citation: Iliopoulou, T.; Dimitriadis, P.; Siganou, A.; Markantonis, D.; Moraiti, K.; Nikolinakou, M.; Meletopoulos, I.T.; Mamassis, N.; Koutsoyiannis, D.; Sargentis, G.-F. Modern Use of Traditional Rainwater Harvesting Practices: An Assessment of Cisterns' Water Supply Potential in West Mani, Greece. *Heritage* **2022**, *5*, 2944–2954. https://doi.org/10.3390/heritage5040152

Academic Editor: Francesco Soldovieri

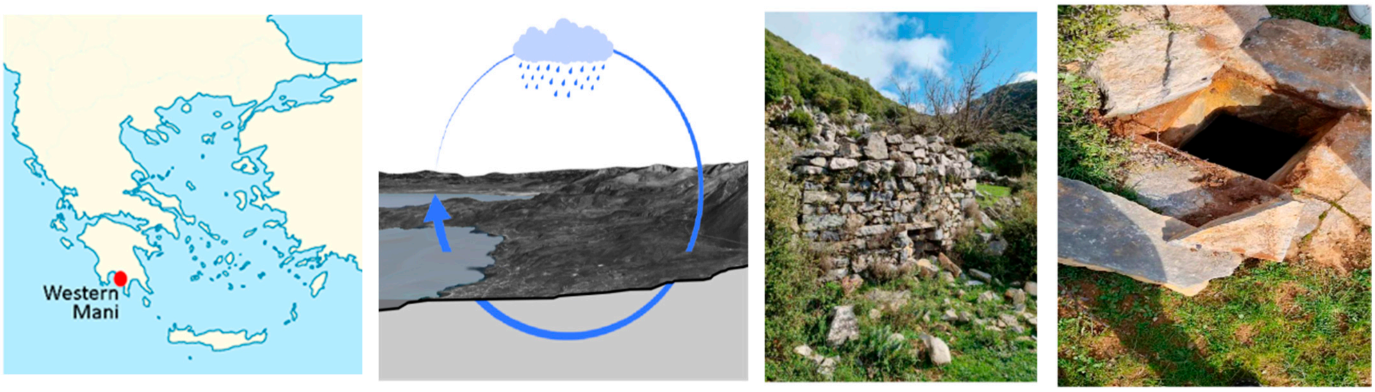
Received: 10 August 2022
Accepted: 26 September 2022
Published: 30 September 2022

1. Introduction

Water, as one of the three critical elements in the water–energy–food (WEF) nexus, has always been a driving force of human civilization [1,2]. The importance of the WEF nexus for social stability and social cohesion was recently highlighted by Sargentis et al. [3] The authors show that although every part of the nexus contributes to increased life expectancy (a prerequisite for societal prosperity), it suffices for one of the nexus' parts to be missing to produce social instability and crisis. This explains why since antiquity human civilizations strived to improve living conditions depending on all three aspects of the WEF, achieving great progress from standards that we would now consider as extreme poverty [3]. Some of the related technological advances, such as the agricultural revolution, were global, while others (e.g., hydraulic infrastructure) covered mostly local needs. In every case, however, the optimization of the WEF nexus was the running paradigm for societies' growth [4–9].

The area of West Mani is located in the southern part of Greece in the Peloponnese and comprises the northwestern part of the Mani region, also known as Outer/Messinian

Mani (Figure 1a). The region has a high rate of precipitation mainly in the mountainous areas. Rainfall is mostly observed during the autumn and winter months, from September to March, while there is significant decrease in the summer. The geological background is extremely permeable as it consists mainly of karstic limestone (Figure 1b), which is typical of the Taygetos mountain [10]. Therefore, only few springs are traced, while the groundwater table is too low to be efficiently exploited by wells, and groundwater mostly outflows to submarine springs. Still, the area has an advantageous location and excellent climatic conditions for human prosperity, and thus, despite the limited surface water resources, it has a long history of inhabitance since the archaic era [11].



(**a**) (**b**) (**c**) (**d**)

Figure 1. (**a**) Location of West Mani in Greece; (**b**) hydrological cycle where water is lost by the permeable geological background in West Mani; (**c**,**d**) views of abandoned cisterns in the Lagadas region.

Due to the extremely permeable background and the mountainous topography, the surface water resources have always been scarce, forcing locals to find ways to harness and store rainwater. Generally, central and eastern Greece suffers from limited water availability and, since prehistory, Greeks have developed hydraulic technology and water management practices to tackle this issue [12–17]. For instance, methods like cisterns (in modern Greek *στέρνες*; Figure 1c) [18] or a process of groundwater capture (in Greek called *υδρομάστευση*) [19] have been used since antiquity for the water supply of the urban areas and villages. However, in the present-day, the majority of the cisterns have been either abandoned or are not functional (e.g., Figure 1c).

The cistern is an underground tank with volumes between a typical range of 5 and 55 m^3 [20] that stores rainwater collected on the roofs of house complexes [21]. Different typologies of a cistern can be found in the wider area of Messinia across the centuries (e.g., ancient Greek, Byzantine, Ottoman, Frankish) [22], but here, we refer to the domestic-scale cistern, usually an underground structure that was in wide use during the 19th century in the area West Mani [22,23]. A cross-section of a traditional tower-house complex with a cistern, illustrating the function of the latter, is presented in Figure 2. This small-scale infrastructure was the basic water source for the local society [24] until the last century [25].

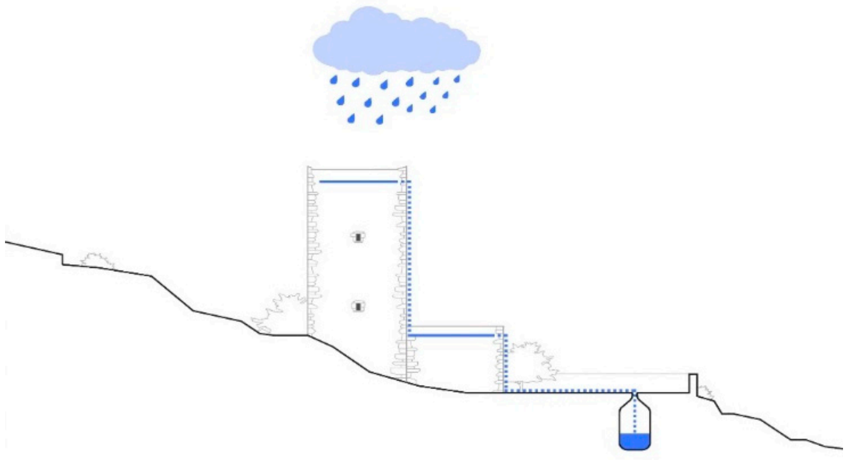


Figure 2. Cross-section of a typical traditional tower-house complex with its cistern in West Mani.

In order to model the cisterns' function as a water supply, we present in Section 2 a long-term simulation of the cistern system based on a stochastic model of monthly rainfall, reproducing the area's rainfall key statistical properties. In Section 3, we estimate the reliability of the water supply system and identify the systems' failures, whereas in Section 4, preceding the conclusions, we discuss and highlight the cultural heritage of the area and its links to the water availability characteristics.

2. Simulating at-Site Monthly Rainfall Using a Stochastic Approach

The cistern's function relies on the rainfall process, which due to limited at-site data, and in order to account for the enriched variability of climatic conditions, herein is modeled via a stochastic approach. The closest meteorological station of Kardamyli [26] in West Mani has only 8 years of rainfall data (2014–2021), which are considered generally insufficient for the estimation of rainfall's long-term stochastic properties. Therefore, we employ the second closest available meteorological station of Kalamata, the rainfall time series of which span 68 years (1951–2018) of data recorded at approximately the same altitude (13 m) [27]. We find a good agreement between the monthly averages of the two stations (Figure 3), and therefore, we employ Kalamata's station for the rest of the analysis, by assuming a similar rainfall regime between the two regions.

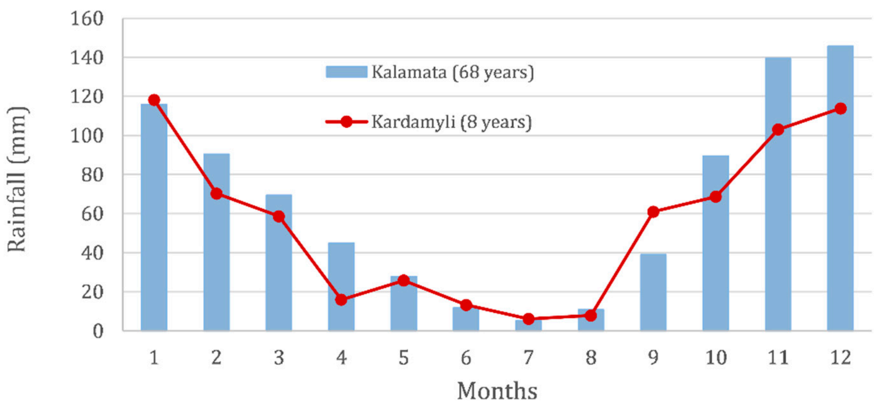


Figure 3. Monthly average of rainfall depths in Kardamyli and Kalamata stations.

An important stochastic property of various natural processes is their large long-term variability, known as Hurst–Kolmogorov (HK) dynamics, or else long-range dependence or long-term persistence (LTP) [28]. This behavior of natural systems was first identified in nature by H.E. Hurst in 1951, while working at the river Nile, although its mathematical description is attributed to A.N. Kolmogorov, who developed it while studying turbulence in 1940. Koutsoyiannis named this behavior Hurst–Kolmogorov dynamics (HK) to give credit to both pioneering scientists [29]. Interestingly, this behavior has been identified in key hydrological-cycle processes at a global scale through the analysis of thousands of stations [30].

Although in HK dynamics the marginal distribution of the process may be arbitrary, the most commonly used distribution is the Gaussian one, which results in the well-known fractional Gaussian noise described by Mandelbrot and van Ness [31], i.e., the power-law decay of variance as a function of scale $\gamma(k)$ [32]. The HK behavior is quantified by the Hurst parameter H ($0 < H < 1$). In the simplest case, the variance $\gamma(k)$ of the process at timescale k, known as the climacogram, is given by

$$\gamma(k) = \frac{\lambda}{(k/\Delta)^{2(1-H)}} \quad (1)$$

where Δ is a characteristic timescale and λ is the variance at this timescale. For $0 < H < 0.5$ the HK process exhibits an anti-persistent behavior, $H = 0.5$ corresponds to the white noise process, and for $0.5 < H < 1$ the process exhibits LTP (i.e., a clustering behavior).

In order to account for a natural behavior deviating from a simple white-noise process (i.e., independence among successive values of the process), we simulate the rainfall using a stochastic model reproducing the HK dynamics. To this aim, we first estimate the H parameter through the climacogram and find that the HK behavior is apparent at the largest scales, as expected (Figure 4). The H parameter, considering the range of scales k = 36–81, is estimated H = 0.6, while considering the range k = 48–81 it increases to H = 0.7. It is noted that there seems to be a small drop of the variance expanding from the small scales to around 3 years, a known behaviour documented in rainfall stochastic analyses in the literature [33].

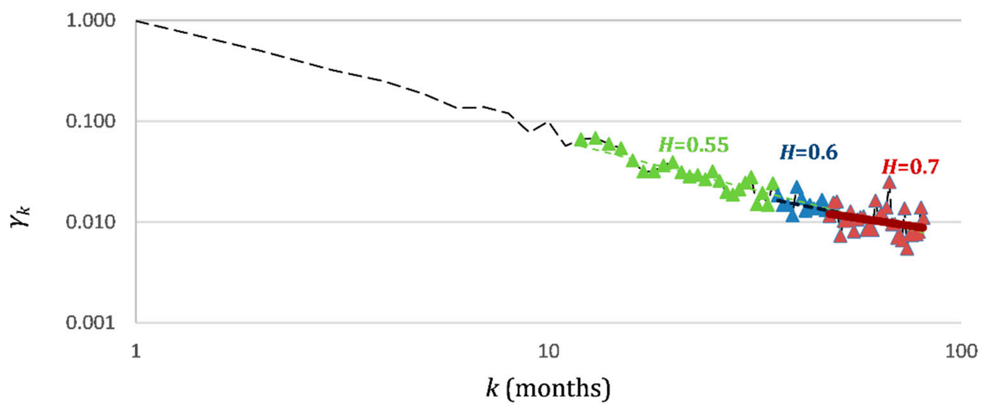
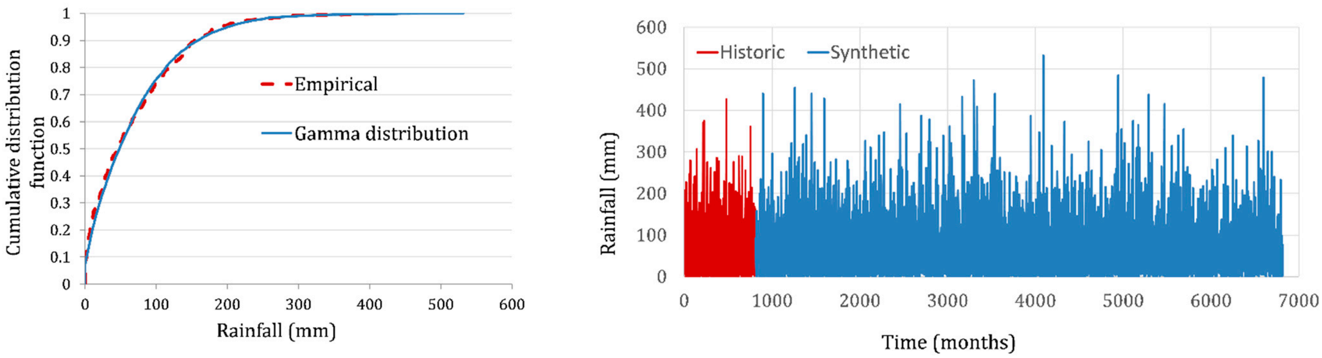


Figure 4. Climacogram of the standardized monthly rainfall series and estimated H parameters based on the yearly (k = 12–81) series (green), series of scales k = 36–81 (blue) and of scales k = 48–81 (red).

Based on these analyses, we employ the value of H = 0.65, also considering that it is a value in accordance with global analyses of rainfall [34]. To model the marginal distribution of the monthly rainfall we use the gamma distribution, which showed a good agreement with the empirical data (Figure 5a). Both the marginal distribution and the identified dependence structure are reproduced through a stochastic synthesis algorithm, and particularly through the symmetric-moving-average (SMA) scheme [35], an established method to simulate hydrological processes as rainfall. We note, however, that more sophisticated schemes exist if one aims for greater accuracy and capturing of finer-scale behaviors [36]. Rainfall seasonality is preserved through a linear standardization procedure, i.e., subtracting from each month its monthly mean and dividing by its monthly standard deviation, and at the end, is recovered by the reverse procedure. Figure 5b shows the synthetic timeseries sharing the above stochastic properties with the historical [37].



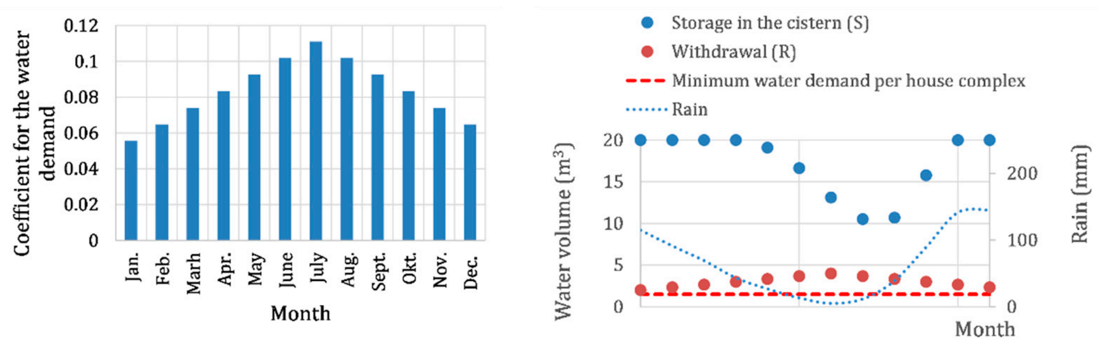
(**a**) (**b**)

Figure 5. (**a**) Empirical (red) vs. gamma (blue) cumulative distribution functions for monthly rainfall at Kalamata. (**b**) Historic (68 years; red) vs. synthetic (500 years; blue) monthly rainfall time series for the station of Kalamata.

3. A Toy Model of the Cistern

Since ancient times, people developed a practical understanding of nature's long-term variability and identified the need to store their water resources when there was abundance thereof, in order to use them when there was scarcity [38–41]. The first written reference of this concept was recorded in the Bible, where Joseph advised the Pharaoh to store the food in wealthy years, as he predicted that dry years would come [42]. This is the reason why LTP is also known as the Joseph effect [43].

In our model, we assume that ten people live in a traditional house complex. The annual water demand is assumed fixed for a given simulation, while the monthly demand is periodically varying, increasing in the summer months and decreasing in the winter months (Figure 6a). The inflows to the cistern are collected at the roofs of the house complex, comprising an area of around 100 m^2. We assume that a percentage of the rainwater as high as 90% enters into the cistern. The lower threshold for drinking water supply for the modern standard of living is assumed at 5 L per capita per day, i.e., 1.5 m^3 per house complex (10 people) per month. We also assume a maximum capacity of the cistern to be 20 m^3.



(**a**) (**b**)

Figure 6. (**a**) Percentage of the annual demand for each month; (**b**) the volume function of the cistern based on average rainfall inflows.

The water storage and withdrawal processes are modeled by the following equations:

$$\underline{S}_T = \max(0, \min(K, \underline{S}_{T-1} + \underline{x}_T - \underline{R}_T) \quad (2)$$

$$\underline{R}_T = \max(0, \min(a_T D,\ \underline{S}_{T-1} + \underline{x}_T) \quad (3)$$

where T denotes time; $\underline{S}_T$ is the storage in the cistern; $\underline{x}_T$ is the rainfall inflow; $\underline{R}_T$ is the water withdrawal (consumption) dependent on the annual demand D and a_T is a set of 12 coefficients periodically varying with time (Figure 6a); and K is the storage capacity, here assumed 20 m^3 [43]. An example of the average monthly function of one cistern's storage volume with an annual demand of $D = 36$ m^3 is presented in Figure 6b.

We define and study the probability of two different types of failure for the system: (a) the cistern's soft failure, defined as the probability of not meeting the entirety of the users' demand per month, and (b) the cistern's hard failure, defined as the probability of not meeting the minimum of the users' monthly demand for survival (here, estimated as 1.5 m^3). Based on the above, we analyze the system's performance for three different scenarios of annual demand D:

- for $D = 36$ m^3 the average consumption is 3 m^3 per month, the system's soft failure is 0.08%, while its hard failure is 0.02% (Figure 7);
- for $D = 54$ m^3 the average consumption is 4.4 m^3 per month, the system's soft failure is 3.17%, while its hard failure is 0.88% (Figure 8);
- for $D = 72$ m^3 the average consumption is 5.6 m^3 per month, the system's soft failure is 9.8%, while its hard failure is 3.13% (Figure 9).

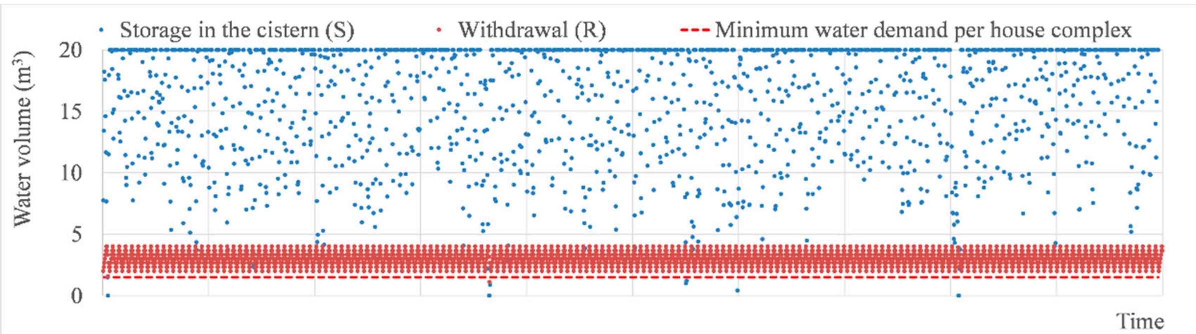


Figure 7. An example of a simulation with annual demand $D = 36$ m^3, corresponding to average monthly consumption of 3 m^3 and with a hard failure estimated as 0.02%.

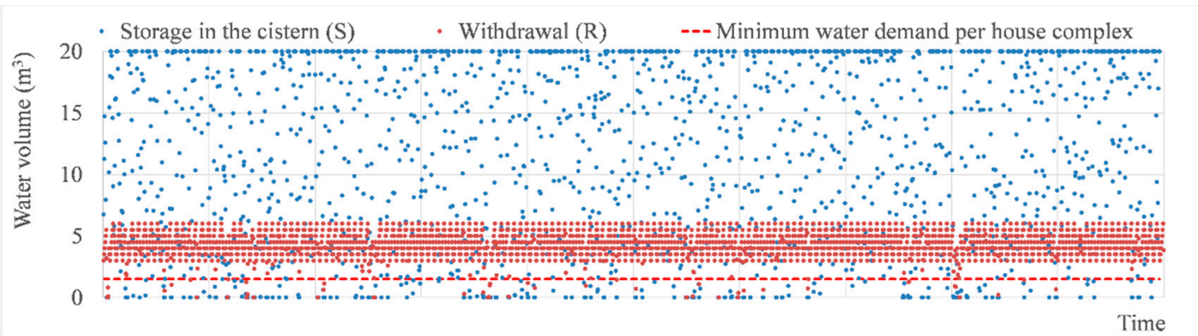


Figure 8. An example of a simulation with annual demand $D = 54$ m^3, corresponding to average monthly consumption of 4.4 m^3 and with a hard failure estimated as 0.88%.

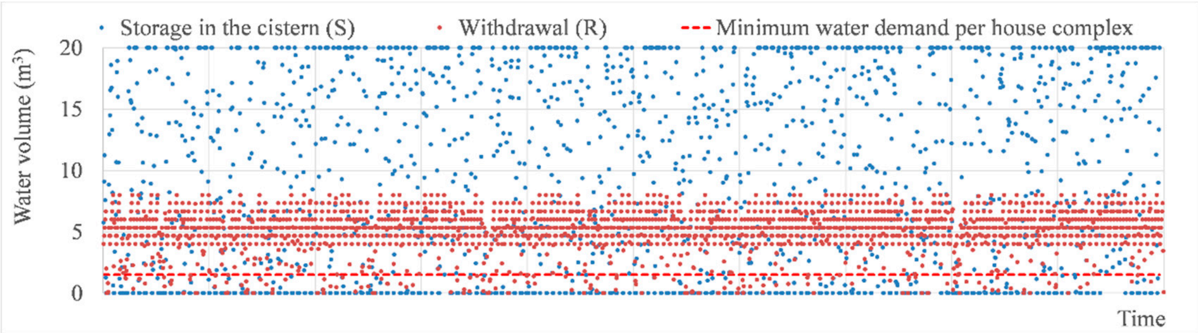


Figure 9. An example of a simulation with annual demand $D = 72$ m^3, corresponding to average monthly consumption of 5.6 m^3 and with a hard failure estimated as 3.13%.

It is evident that the system's reliability is very sensitive to changes in demand, which, of course, is an expected attribute of small-scale infrastructure systems [44]. It is therefore clear that neither the modern way of living nor future growth could be supported by such a system alone. Yet despite the sharp increase in both hard and soft failure for increasing demand, the hard failure rate remains at acceptable levels for all three cases. The latter suggests that the cisterns' revival as a complementary backup water system could be a sustainable strategy for the future. It could also positively contribute to the survival and growth of the local communities, by reducing the drinking water cost (now covered by the purchase of bottled water) while increasing the locals' resilience against possible failures of the central water-supply system [45]. Nonetheless, the architecture of cisterns is well-suited to the local landscape, while their historic and cultural elements, which are discussed next, highilight and promote the cultural heritage of the area.

4. Discussion

Water is the most precious resource for human life, and its availability shapes both the way of living and the cultural traits of local communities. The availability of water resources in West Mani has been extremely limited and documented as such in various historical archives; e.g., Adamakopoulos notes [46]:

> "The bare landscape and barren lands of Mani, would be less harsh to humans if this place had even sporadically, a spring or a stream. Made of the same permeable limestone, the mountains of Mani cursed people to beg for the mercy of the sky. Apart from Avia and a part of the Kardamili area, many villages of Exo (Outer) Mani and whole Mesa (Inner) Mani, lived with the anticipation of the rain and the measurement of the level of the cistern." (translated from the Greek original)

Indeed, until the 19th century the cistern was the basic source of drinking water in the Mani Peninsula and also supported the development of domestic-scale livestock and agriculture [22,23,47]. However, some other small-scale water infrastructure can also be found in the area, such as drinking water fountains utilizing natural springs of very small flows and small stone-lined ponds, which harvested rainwater for irrigation purposes [21]. Still, water scarcity remained pronounced in the area and contributed, among other adverse factors, to cultivating a renowned fierce character of the inhabitants and a "fighting" culture, even among themselves [48]. Not surprisingly, inhabitants of West Mani played a key role in starting the Greek Revolution in 1821 [24,47,49,50].

The previous analyses show that a cistern could support the drinking water needs for about 10 people with a simple way of living. However, the consumption of water in preindustrial eras was mostly dominated by drinking water consumption, which (depending on the season) is about 2–5 L per day [51]. In modern times, this daily average consumption is greatly increased, as a modern way of living requires a minimum of 50–150 L per day [52]. Considering that the area of West Mani has evolved into an attractive tourist destination and a lot of tourist infrastructures have installed water pools, we assume that the daily consumption per capita can be estimated to be at least 250–350 L.

In the last 50 years, modern borehole infrastructures have been installed in the area in order to cover the water needs by extracting groundwater, albeit with low water quality [53]. As a result, inhabitants and tourists are still advised to drink only bottled water, which typically costs about 1 €/L. Other technical solutions that have been proposed are not expected to result in better water quality and mostly aim to only partially address the problem of limited quantity [54,55].

In this light, a proper restoration of the cisterns [56] could give an important supply of drinking water to the locals. It is important to note that, according to the model, after a proper restoration, a cistern of 20 m^3 could provide as much as 36,000 L of drinking water per year. At the same time, it is worth noting that the cistern, as a domestic-scale underground water tank, is a low-cost construction, fully integrated into the local landscape.

From a cultural perspective, the cisterns constitute an important element of West Mani's traditional architecture [57], which is highly valued by modern-day visitors [58]. They also point to an essential part of the local history, representing the striving for water from antiquity to the 20th century. A restoration thereof, apart from contributing to the water supply an important source of drinking water, could reconnect the locals to a more sustainable way of living, improving their resilience under future water shortages. Restored cisterns could act as a modern reminder of the adversely dry climate and the human struggle for survival in the area, both of which shape the area's unique cultural heritage.

5. Conclusions

We evaluate the water supply operation of the traditional rainwater harvesting practice of cisterns in West Mani, one of Greece's areas with a pronounced water shortage. A simple water management assessment using rainfall stochastic simulation and a toy model for the cistern operation shows that even though cisterns alone cannot support the modern way of living, their function could still efficiently complement the existing water supply system, even if it is re-evaluated with economic criteria. Indeed, the cisterns could be an important low-cost and backup source of drinking water that would reduce the drinking water cost in the area. At the same time, the cisterns' operation as a domestic practice would cultivate the locals' awareness of the limited water resources and their dynamics, also increasing their resilience under future water shortages.

From a historical investigation, it becomes apparent that the cistern was a crucial means for survival of the local societies against water shortage, which formulated the culture and ethos of the area's inhabitants. In fact, major events of the history of Greece can be linked to this quest for water in West Mani. Therefore, cisterns, aside from a sustainable practice of water supply, are shown to be an important element of West Mani's unique cultural heritage.

Author Contributions: Conceptualization, G.-F.S., T.I., P.D., A.S., D.M., K.M., M.N., I.T.M., N.M., D.K.; methodology, G.-F.S., T.I., P.D., A.S., D.M., K.M., M.N., I.T.M., N.M., D.K.; validation, G.-F.S., T.I., P.D., A.S., D.M., K.M., M.N., I.T.M., N.M., D.K.; formal analysis, G.-F.S., T.I., P.D., A.S., D.M., K.M., M.N., I.T.M., N.M., D.K.; investigation, G.-F.S., T.I., P.D., A.S., D.M., K.M., M.N., I.T.M., N.M., D.K.; data curation, G.-F.S., T.I., P.D., A.S., D.M., K.M., M.N., I.T.M., N.M., D.K.; writing—original draft preparation, G.-F.S., T.I., P.D., A.S., D.M., K.M., M.N., I.T.M., N.M., D.K.; writing—review and editing, G.-F.S., T.I., P.D., A.S., D.M., K.M., M.N., I.T.M., N.M., D.K.; visualization, G.-F.S., I.T.M., T.I.; supervision, G.-F.S., T.I., P.D., A.S., D.M., K.M., M.N., I.T.M., N.M., D.K. All authors have read and agreed to the published version of the manuscript.

Funding: The students involved in this research, namely, A.S., D.M., K.M. and M.N., were funded by the Municipality of West Mani.

Data Availability Statement: The databases that have been used are referred to in detail in the citation given in the text and are publicly available.

Acknowledgments: We are grateful to the eponymous reviewers for their thoughtful and constructive comments that improved the manuscript. We thank the Municipality of West Mani for providing financial support to the students involved in this research. We also thank Michalis Chiotinis for his notable comments.

Conflicts of Interest: The authors declare no conflict of interest.

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