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Effect of Rainfall Regime on Rainwater Harvesting Tank Sizing for Greenhouse Irrigation Use

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Abstract: The use of rainwater harvesting tanks to supply human water needs is an old and sustainable practice. In the case of covering irrigation demand in greenhouse agriculture, the potential is huge. Still, the relative research worldwide is low, while it is nearly absent in Greece. In this study, the rainwater harvesting tank size for irrigation use of greenhouse tomato cultivation was investigated by applying a daily water balance model in three regions of Crete Island (Greece) with significant greenhouse areas. Daily rainfall data from three representative rainfall stations of the study areas characterized by different rainfall regime for a 12-year time series were used. Additionally, the daily irrigation water needs for a tomato crop during an 8-month cultivation period were used. The greenhouse roof was defined as catchment area of the rainwater harvesting system and greenhouse areas of 1000, 5000 and 10,000 m^2 were studied. In all areas examined, a tank of 30–100 m^3 per 1000 m^2 of greenhouse area could reach approximately 80–90% reliability. Higher values of reliability (reaching 100%) could be achieved mainly with covered tanks. Tank size for 100% reliability in covered tanks, ranged from 200 m^3 (per 1000 m^2 of greenhouse area) in the study area with high mean annual rainfall depth (974.24 mm) and moderate mean longest dry period (87.67 days), to 276 m^3 (per 1000 m^2 of greenhouse area) in the study area with relatively low mean annual rainfall depth (524.12 mm) and high mean longest dry period (117.42 days). For uncovered tanks, a 100% reliability value could be reached only with a tank size of 520 m^3 (per 1000 m^2 of greenhouse area) in the study area with high mean annual rainfall depth and moderate mean longest dry period.

Keywords: daily rainfall; dry period; water balance model; rainwater tank size; reliability coefficient; greenhouse; irrigation needs; tomato crop

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1. Introduction

The ever-increasing demands for water for domestic and agricultural use due to climate variability, growing population and increased food production, press the already burdened existing water resources, making the need to find alternatives and sustainable water sources [1–4]. Rainwater harvesting, although it is an ancient practice of water management, currently gains increasingly more ground as a sustainable source of water, providing autonomy in its management.

With agriculture being the main consumer of water in several countries, many of them have highlighted the benefits of rainwater harvesting systems and promoted their use in agriculture [5]. In Greece, irrigated agriculture is also the main water consumer, while the adoption of rainwater harvesting technique is at low levels and there is no research on tank sizing and harvesting potential. Greenhouse agriculture is the main sector that uses the rainwater harvesting technique. Greenhouse area in Greece covers approximately 7100 ha [6].

Greenhouses on the island of Crete cover approximately 2800 ha [6]. Rainwater harvesting is popular among greenhouse holdings, both because of water scarcity and centuries of tradition. Thus, special care is taken, in the measures of the Water Framework

Directive Local Management Plan, to ease the use of rainwater harvesting tanks. More specific, in an arrogation of the standard procedure, no special license for the installation of a tank is required, provided that the tank: (a) is filled only with rain harvested from rooftops of greenhouses, (b) serves the irrigation needs of them and (c) has a storage volume that is up to 500 m^3 per 3000 m^2 of roof [7].

Recently, a review of the last 20 years of global research on the use of rainwater harvesting for irrigation purposes was performed by Velasco-Munoz et al. [8]. One of the key findings referred to the low level of this technique's use for greenhouses, despite the fact that it requires low investments and has a profoundly large potential to collect rainwater.

Additionally, only a few studies have been performed on this issue. Singh et al. [9] found that 60% of the irrigation needs of a sweet pepper crop could be met by a tank of 125 m^3 per 560 m^2 greenhouse area in Ludhiana district (India), with a mean annual 781.5 mm rainfall. In contrast, Boyaci and Kartal [10], in their study in Kırşehir province (Turkey) with low annual rainfall (i.e., 388.3 mm), presented that 61.49% and 47.74% of the tomato crop irrigation needs in heated and unheated greenhouses, respectively, could be met by tanks with capacities of 0.21 and 0.30 m^3/m^2, respectively. Londra et al. [11] studied the reliability of rainwater tanks to meet the irrigation needs of begonia and tomato crops in two regions of Greece with low annual rainfall (419 mm and 448 mm). They found that 65 to 72% of the irrigation needs of the begonia crop during a 12-month growing season could be met by covered tanks 100 to 200 m^3 per 1000 m^2 greenhouse area, respectively. On the other hand, 90 to 100% of the irrigation needs of tomato crop during a 8-month cultivation period could be met by covered tanks 100 to 290 m^3 per 1000 m^2 greenhouse area, respectively, while the maximum value of the irrigation needs that could be met by uncovered tanks was 91% with a critical tank capacity of 177 m^3 per 1000 m^2 of greenhouse area.

Considering that the size of rainwater tanks is strongly influenced by the local weather conditions of the region where the tanks will be established [12–16], the local characteristics related to the greenhouse and rainwater tank infrastructure, and the cultivated crops and their irrigation needs, the application of an appropriate daily water balance model for determining the tank size is needed [11].

Concerning the quality of the harvested rainwater for irrigation use, the basic requirements include low to medium salt content and low content in heavy metals and total coliforms [17]. Many studies confirm that the quality of the harvested rainwater is generally suitable for irrigation use according to the abovementioned requirements [18–20].

The purpose of this study is to investigate the effect of rainfall regime on rainwater tank sizing for meeting greenhouse tomato crop irrigation needs on Crete Island (Greece), a region that is characterized by both extensive greenhouse development and important infrastructure of rainwater harvesting systems. A daily water balance model is applied for sizing covered and uncovered rainwater tanks using daily rainfall data from three stations with different rainfall regimes.

2. Materials and Methods

2.1. Study Area

2.1.1. Greenhouse Cultivated Crops

In Greece, the horticultural areas that are used to grow vegetables cover 57,442 ha, from which 7067 ha are covered by vegetables grown in greenhouses [6]. It is worth noting that 40% of the vegetables cultivated on Crete Island are grown in greenhouses, with the tomato crop being dominant [6] (Figure 1). Consequently, based on the abovementioned data for greenhouse agriculture development in Greece, Crete Island was selected as the study area and the greenhouse tomato crop was examined.

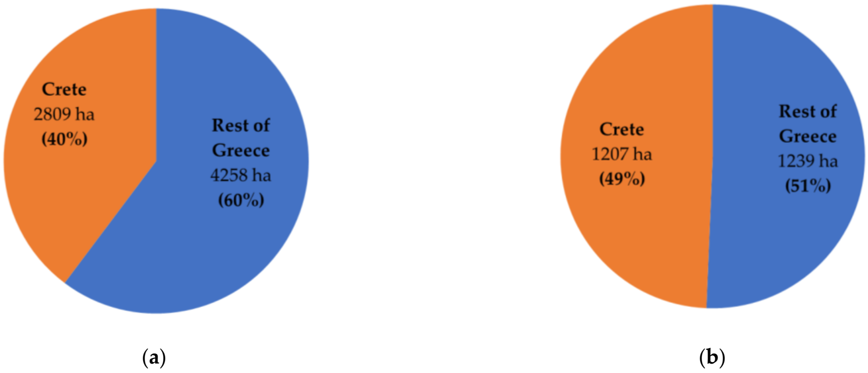


Figure 1. Greenhouse cultivation areas by (**a**) vegetables and (**b**) tomatoes on Crete Island in relation to the rest of Greece.

2.1.2. Rainfall Characteristics

Crete Island is located in the southern part of Greece, approximately between the 23 to 26 parallel E and 35 N. The climate of Crete is typically Mediterranean, which means that the year is divided roughly into two seasons. The first is characterized as a cold and rainy season that lasts from mid-October to late March, with the coldest months being January and February. The second season is characterized as warm and dry, lasting from April to September, with the warmest months being June, July and August. Furthermore, throughout the year, extended time periods with sunshine are observed, making it easy for crops to grow.

Within the Mediterranean climate frame, due to strong relief with a special vertical and horizontal division of Crete Island, a variety of rainfall regimes are found in several regions. Annual rainfall, in general, increases with the altitude and decreases from the western to the eastern parts of the island. Rainfall ranges from less than 400 mm in the SE areas to more than 2000 mm over the mountains of western Crete (Lefka Ori). In low altitude areas, where greenhouse agriculture has expanded, it ranges roughly from 400 to 900 mm [21].

Three rainfall stations, Vrysses, Palaiochora and Moires, in different areas of Crete with different rainfall regime and greenhouse development and rainwater harvesting tanks installations, were selected based on both the availability of daily rainfall data and the completeness of rainfall time series (Table 1, Figure 2). Additionally, the selection of these rainfall time series was made cautiously in order to incorporate prolonged drought periods for addressing, as best as possible, this risk factor in the tank-size calculation process. The daily rainfall data were obtained from the database of the National Observatory of Athens [22] for the time period 2008–2020 (for the stations Vrysses and Palaiochora) and 2009–2021 (for the station Moires). These time periods of twelve years satisfy the minimum required period of rainfall data (i.e., 10 years) for sizing the rainwater harvesting tank [23].

Table 1. Rainfall stations characteristics.

Rainfall Station (Crete, Greece)	Altitude (m)	Longitude (deg)	Latitude (deg)
Vrysses	58	24.22960	35.36430
Palaiochora	5	23.68459	35.23750
Moires	54	24.83459	35.03007

Additionally, the mean annual rainfall values and the longest annual dry periods (i.e., the maximum time period without rain or effective rainfall depth less or equal to 1 mm) were calculated for all stations studied [12].

Figure 2. Rainfall stations studied on Crete Island, Greece.

2.2. Rainwater Harvesting Tank-Sizing Method

For sizing the rainwater harvesting tanks to meet the irrigation needs of tomato crops in greenhouses, a daily water balance model reported by Londra et al. [11] was applied. Specifically, the model takes into consideration the daily rainfall and evaporation data, the greenhouse rooftop (as the catchment area for rainwater) and its runoff coefficient, the tank volume, and the irrigation needs. The model is described by the following equation [11]:

$$S_t = S_{t-1} + R_t - D_t - E_t \quad 0 \le S_{t-1} \le V_{tank}, \tag{1}$$

V_{tank} (m^3) is the capacity of the rainwater tank and the S_{t-1} and S_t (m^3) are the stored rainwater volumes within the tank at the beginning and the end of tth day, respectively.

R_t (m^3) is the rainwater volume that is harvested from the greenhouse rooftop A (m^2) during the tth day, considering its runoff coefficient C (-) and the daily rainfall depth P_t (m), and can be computed as:

$$R_t = C \cdot A \cdot P_t, \tag{2}$$

Considering that the greenhouses studied are made from plastic, the C value used was 0.9 [24].

D_t (m^3) is the water demand for covering the irrigation water needs of the greenhouse tomato plants during the tth day, and is calculated as:

$$D_t = I_{r1} + C_c \cdot A \cdot I_{r2,t}, \tag{3}$$

C_c (-) is a coefficient equal to 0.9 and is referred to as the percentage of the greenhouse area A (m^2) covered by tomato plants. The water demand refers to the amount of water needed to meet the irrigation needs both at the beginning of each new growing season by supplying the soil with the necessary available water content, I_{r1} (m), and the daily irrigation needs of tomato plants during the cultivation period, $I_{r2,t}$ (m). Taking into account an 8-month tomato cultivation (lasting from early October to late May) in a plastic and unheated greenhouse on Crete Island, the aforementioned irrigation needs were defined as I_{r1} = 0.042 m, and $I_{r2,t}$ ranged from 0.0004 to 0.0008 m day^{-1} during the first five months

(October to February) and from 0.002 to 0.003 m day^{-1} during the last three months (March to May) [11,25].

E_t (m^3) is the daily evaporation that is considered only in the case of uncovered rainwater harvesting tanks.

Overall, substituting Equations (2) and (3) into Equation (1), the equation of the water balance model is given as:

$$S_t = S_{t-1} + C \cdot A \cdot P_t - I_{r1} - C_c \cdot A \cdot I_{r2,t} - E_t, \tag{4}$$

During the computation process of the daily stored rainwater, the iterative heuristic algorithm presented by Londra et al. [11] was applied considering the capacity of the rainwater harvesting tank, V_{tank}. The daily overflowed rainwater volume, O_t (m^3), or the daily water volume of unserved demand, T_t (m^3), from the stored rainwater was also computed from the following algorithms:

$$if\ S_t \succ V_{tank}\ then\ V_{tank},\ if\ S_t \prec 0\ then\ 0\ else\ S_t, \tag{5}$$

$$if\ S_t \geq V_{tank}\ then\ O_t = S_t - V_{tank}\ else\ O_t = 0\ , \tag{6}$$

$$if\ S_t \prec D_t\ then\ T_t = D_t - S_t\ else\ T_t = 0, \tag{7}$$

In the present study, we assumed an initially full tank, and we examined the representative rainwater collection areas of 1000, 5000 and 10,000 m^2.

Finally, the effectiveness of the rainwater harvesting system was evaluated from a reliability coefficient, *Re*, which indicates the extent to which the available stored rainwater can satisfy the irrigation water demand. *Re* is expressed as the percentage of the days that fully meet the water demand (N_f) in relation to the total simulated days (N_{tot}) and is calculated [11] using the following formula:

$$Re = \frac{N_f}{N_{tot}} \cdot 100\ (\%) \tag{8}$$

The simulated days used were N_{tot} = 4383 days (i.e., 12 years).

3. Results and Discussion

In Figure 3, the distribution of daily rainfall depths of the three rainfall stations examined during the 12-year period used is presented. In all stations, the rainfall is concentrated during the wet period extending from October to April of each year, leaving a distinctive dry period extending from May to September, typical of the Mediterranean climate type. Specifically, at the Vrysses station, the daily rainfall depths have values mainly less than 75 mm and a mean annual rainfall of 974.24 mm, while at the Palaiochora and Moires stations, the daily rainfall depths have low values, mainly < 25 mm, and a mean annual rainfall of 514.12 and 424.12 mm, respectively (Figure 3, Table 2).

To thoroughly study the rainfall regime of the stations used, recognizing that the dry period is the main hydrologic parameter affecting the behavior of a rainwater harvesting system [16], an analysis of the longest annual dry periods was made. As shown in Figure 4a, the Vrysses station has smaller values of the longest annual dry periods than those of the other two stations, and ranges from 41 to 175 days with a mean of 87.67 days (approximately 3 months). In contrast, the Palaiochora and Moires stations, which are similar to each other, are characterized by a larger longest dry period, ranging from 40 to 152 days and 48 to 145 days, respectively (Figure 4b,c), with mean values 117.42 and 111.67 days (approximately 4 months) (Table 2).

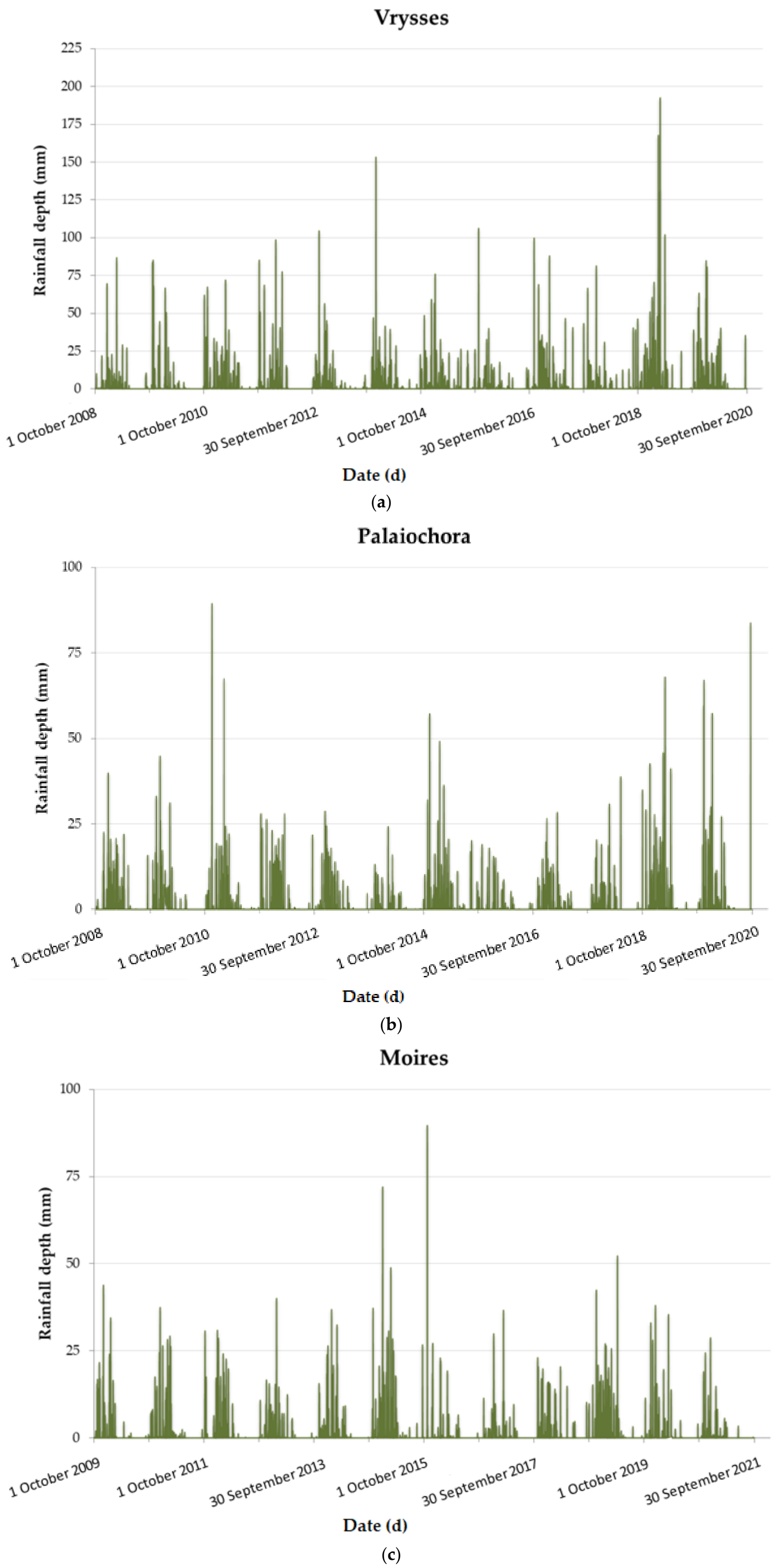


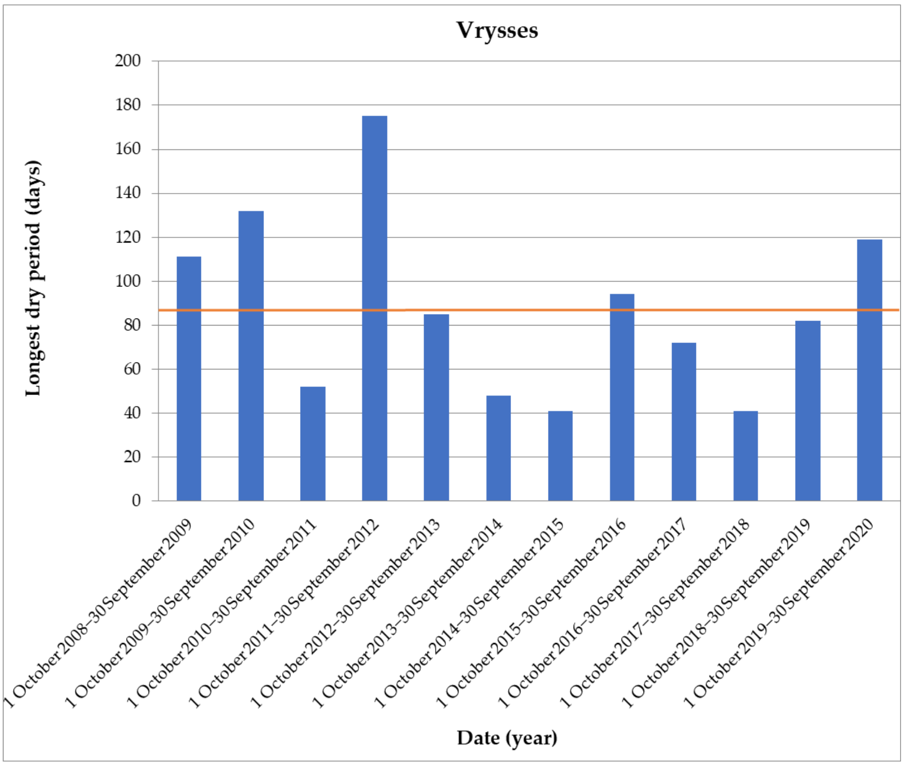
Figure 3. Daily rainfall data for each time period studied at the three stations, Crete, Greece: (**a**) Vrysses, (**b**) Palaiochora and (**c**) Moires.

Table 2. Mean annual rainfall depth (P), maximum ($N_{dd,max}$), minimum ($N_{dd,min}$) and mean (N_{dd}) longest annual dry period for each rainfall station studied. The corresponding standard deviation values, σ_P and $\sigma_{Ndd,}$ are also given.

Rainfall Station	P (mm)	σ_P (mm)	$N_{dd,max}$ (days)	$N_{dd,min}$ (days)	N_{dd} (days)	σ_{Ndd} (days)	Rainfall Time Series
Vrysses	974.24	322.75	175	41	87.67	41.17	2008–2020
Palaiochora	524.12	181.14	152	40	117.42	29.91	2008–2020
Moires	424.53	159.26	145	48	111.67	29.25	2009–2021

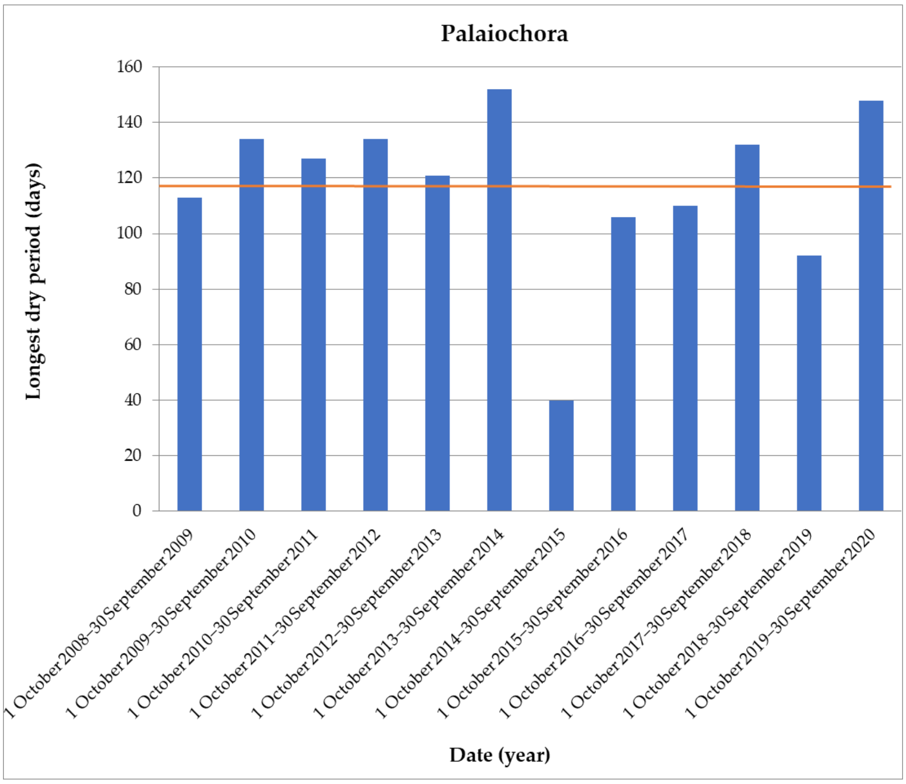
Furthermore, in the case of the uncovered rainwater tank investigation, the required daily evaporation values were calculated from the available monthly evaporation data for the Tympaki station (Crete, Greece) [11,26] (Figure 5).

In Figure 6, the reliability curves of the rainwater harvesting systems with covered and uncovered tanks for meeting the tomato crop irrigation needs for various greenhouse areas in the three regions with different rainfall regimes are presented. In the case of the Vrysses study area with its high mean annual rainfall depth (974.24 mm) and moderate mean longest annual dry period (87.67 days), reliability values greater than 83% are observed. Specifically, covered tanks sized from 100 to 200 m^3 per 1000 m^2 of greenhouse area could meet 95.32% to 100% of the tomato irrigation needs, respectively, while uncovered tanks 100 to 520 m^3 per 1000 m^2 could meet 94.07% to 100% of the irrigation needs, respectively (Figure 6a,b).



(a)

Figure 4. *Cont.*



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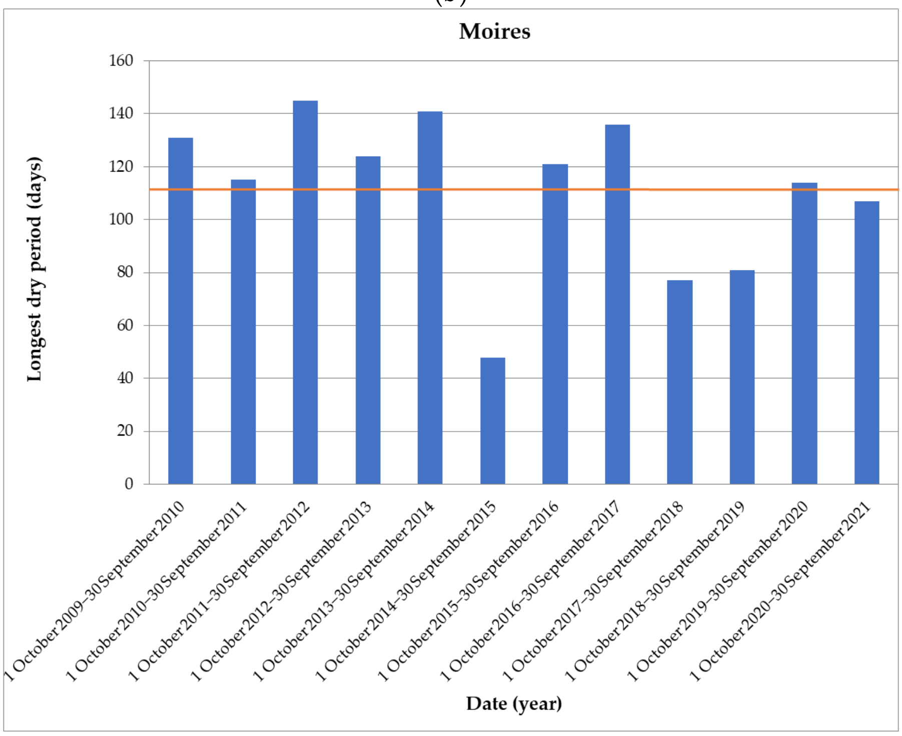


(**c**)

Figure 4. Distribution of the longest annual dry periods in the 12-year period studied for the three rainfall stations, Crete Island (Greece): (**a**) Vrysses, (**b**) Palaiochora and (**c**) Moires. The mean longest annual dry period value for each station is depicted by the horizontal line.

In the other two study areas, Palaiochora and Moires, with rainfall regimes different than Vrysses, lower reliability values are observed, in general. In more detail, in Palaiochora, with its relatively low mean annual rainfall depth (524.12 mm) and high mean longest annual dry period (117.42 days), covered tanks sized from 100 to 276 m^3 per 1000 m^2 of greenhouse area could meet 91.10% to 100% of the tomato irrigation needs, respectively, while uncovered tanks 100 to 227 m^3 per 1000 m^2 could meet 89.05% to 92.95% of the irrigation needs, respectively (Figure 6c,d). The 92.95% is the maximum value that can be achieved by uncovered tanks. Tank volumes greater than 227 m^3 lead to reduced reliability values because greater evaporation losses occur from the free-water surface of the tanks, leaving consequently less stored water in the tanks for satisfying the irrigation needs of the tomato plants.

Finally, in the case of the Moires study area, which is characterized by low mean annual rainfall depth (424.53 mm) and high mean longest annual dry period (111.67 days), covered tanks sized from 100 to 237 m^3 per 1000 m^2 of greenhouse area could meet 89.09 to 100% of the tomato irrigation needs, respectively, while uncovered tanks 100 to 210 m^3 per 1000 m^2 could meet 87.11 to 91.63% of the irrigation needs, respectively (Figure 6e,f). The 91.63% is the maximum value that can be achieved by uncovered tanks (Figure 6f).

A comparison between the covered and uncovered tanks showed that the rational management of stored rainwater was attained by the covered tanks that had greater reliability values, reaching even 100% with a suitable tank capacity. On the other hand, the maximum reliability values of uncovered tanks are 91.63% (Moires) and 92.95% (Palaiochora) for the critical tank volumes of 210 and 227 m^3 per 1000 m^2 greenhouse area, respectively (Figure 6). For tank volumes greater than the critical ones, reduced reliability values of the rainwater harvesting system were computed. The exception is the case of the Vrysses study area, with its high annual rainfall and moderate longest annual dry period, where a reliability value of 100% can be also achieved by uncovered tanks (Figure 6).

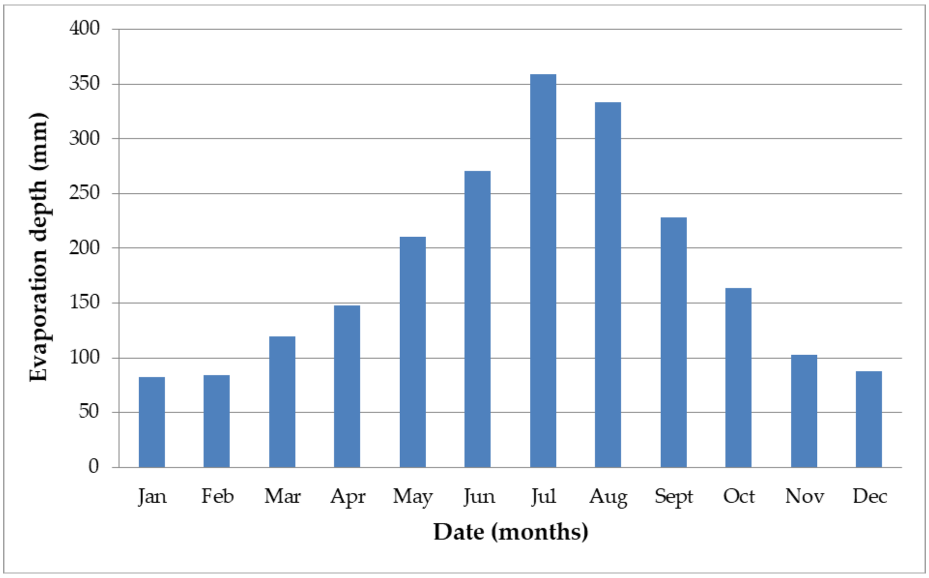


Figure 5. Mean monthly evaporation data.

It is clear that the smallest tank volumes and the greatest reliabilities on meeting the irrigation needs of tomato crops were observed in the area with high annual rainfall depth and moderate dry period. Amongst the study areas with low annual rainfall depth and high dry periods, the small difference of 100 mm in mean annual rainfall and 6 days in mean longest annual dry period contributed to the small differentiation of the reliability coefficients and the required covered tank volumes for fully meeting the irrigation needs or the critical uncovered tank volumes.

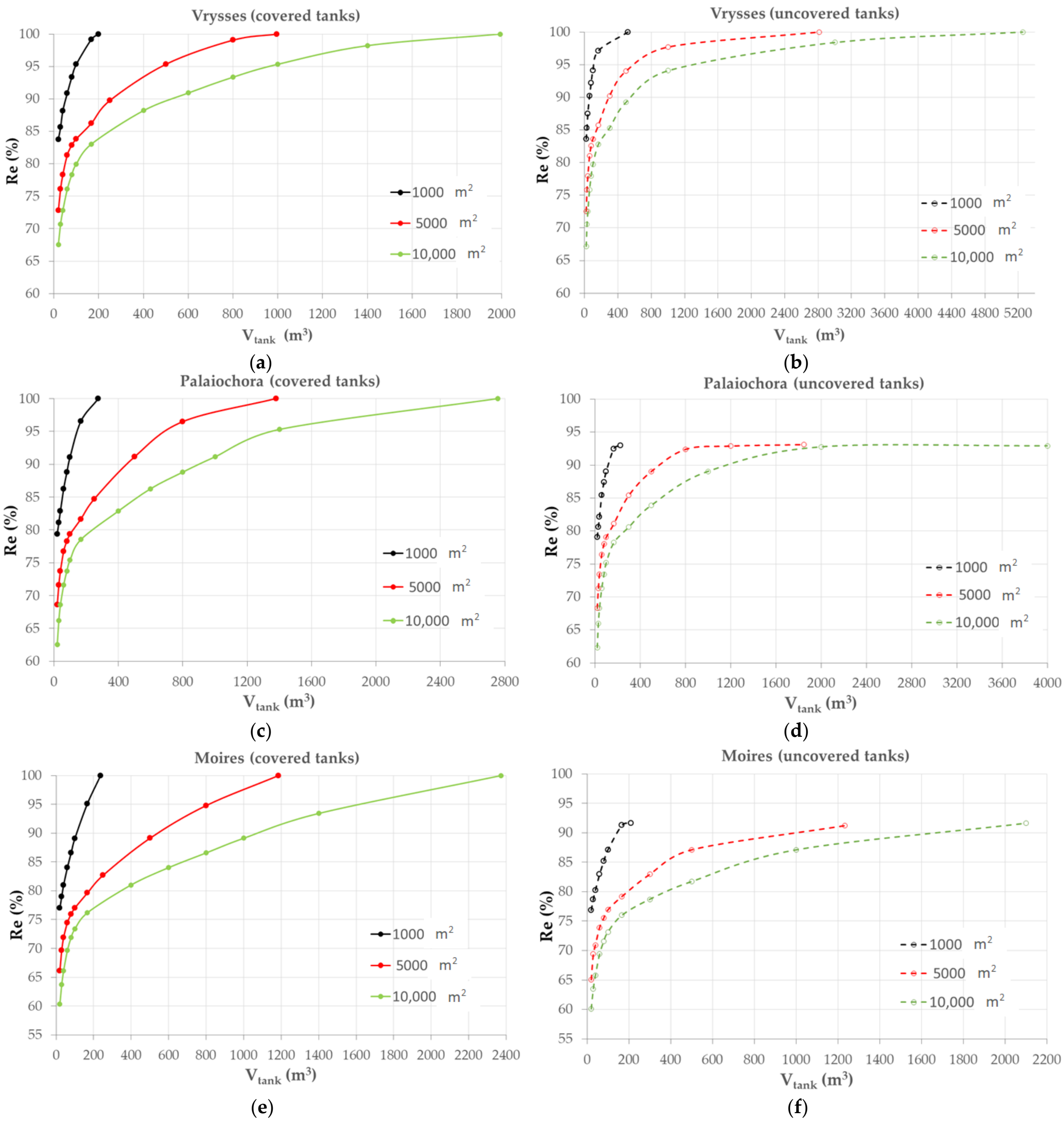


Figure 6. Reliability curves of rainwater harvesting systems with covered and uncovered tanks for meeting the tomato crop water needs for greenhouse runoff covering 1000, 5000 and 10,000 m^2 in the (**a**,**b**) Vrysses, (**c**,**d**) Palaiochora and (**e**,**f**) Moires study areas.

Overall, the tank sizes studied ranged from 20 m^3 per 1000 m^2 greenhouse area to the size that a 100% reliability value was reached. Reliability curves revealed that for both covered and uncovered tanks, a size of 20 to 30 m^3 per 1000 m^2 reached a reliability value of 75% to 80%. A reliability value of 90% could be reached with approximately 100 m^3 per 1000 m^2 both for covered and uncovered tanks, while for 100% reliability, tanks of 200 m^3 to 520 m^3 per 1000 m^2 and beyond, for covered and uncovered tanks, respectively, were needed.

The practical application of these calculations for greenhouse farmers is that a moderately good reliability level (75–80%) can be achieved with a relatively low-cost, small uncovered tank (20–30 m^3 per 1000 m^2 greenhouse area).

Furthermore, a comparative presentation of the relationship $Re(\log V_{tank})$ for all study areas examined is presented in Figures 7 and 8 for covered and uncovered rainwater tanks, respectively. The corresponding diagrams were made considering a maximum value of V_{tank} equal to 100 m^3 per 1000 m^2 greenhouse area, which is a representative and widely used tank volume with high reliability level, i.e., from 89 to 95%. As shown in Figure 7a, the relationships $Re(\log V_{tank})$ for greenhouse area 1000 m^2 are linear and parallel for all study areas, with a mean slope value equal to 17.01 and y-intercept values ranging from 53.871 to 61.405, defined by the rainfall regime of the study areas. Similar results were observed in the cases of the greenhouse areas 5000 and 10,000 m^2. Specifically, the relationships $Re(\log V_{tank})$ for greenhouse area 5000 m^2 have a mean slope value equal to 15.53 and y-intercept values ranging from 46.351 to 53.066 (Figure 7b), and the same relationships for greenhouse area 10,000 m^2 have a mean slope value equal to 15.84 and y-intercept values ranging from 40.615 to 47.661 (Figure 7c).

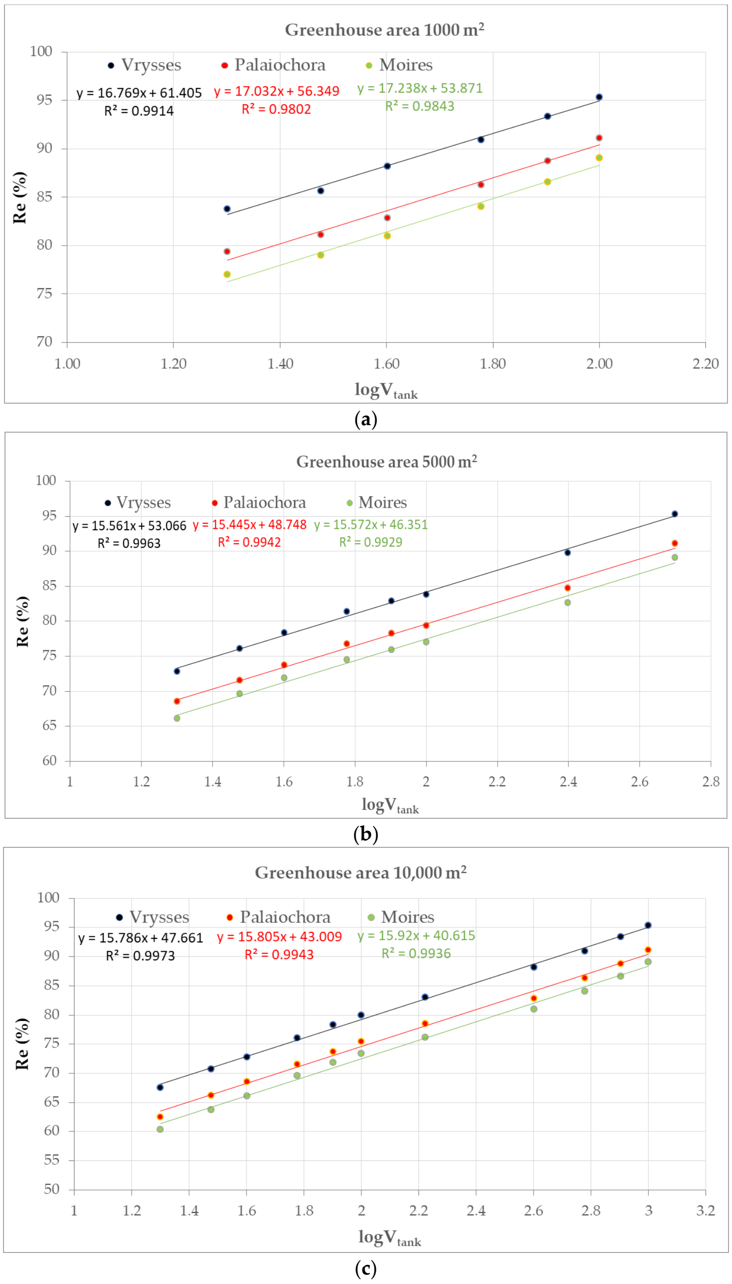
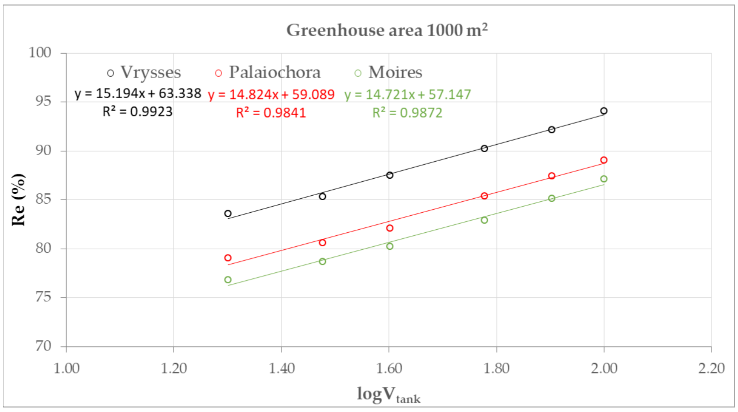


Figure 7. Comparative presentation of the relationships between reliability coefficients and log values of covered rainwater tank volumes, $Re(\log V_{tank})$, for meeting the tomato crop water needs for (**a**) 1000 m^2, (**b**) 5000 m^2 and (**c**) 10,000 m^2 greenhouses in three study areas (Vrysses, Palaiochora and Moires). The volumes of V_{tank} are in m^3.



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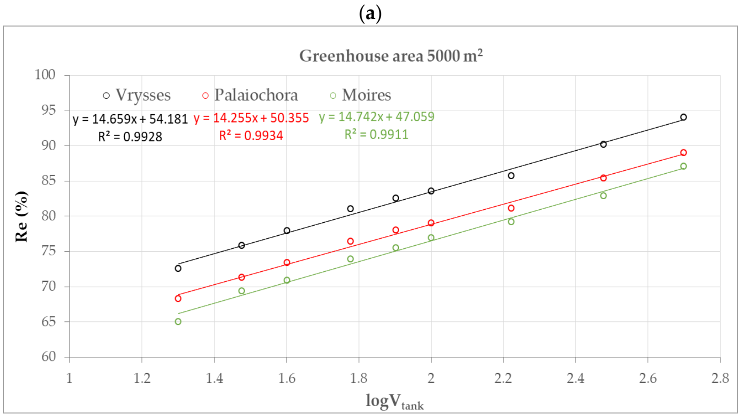

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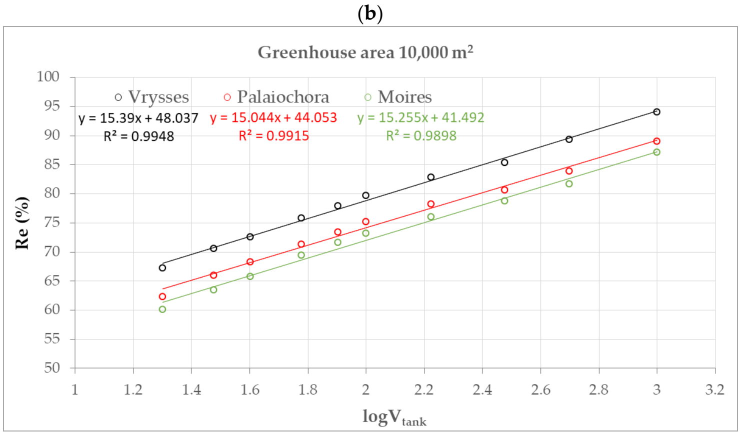

(**c**)

Figure 8. Comparative presentation of the relationships between reliability coefficients and log values of uncovered rainwater tank volumes, $Re(\log V_{tank})$, for meeting the tomato crop water needs for (**a**) 1000 m^2, (**b**) 5000 m^2 and (**c**) 10,000 m^2 greenhouses in three study areas (Vrysses, Palaiochora and Moires). The volumes of V_{tank} are in m^3.

Corresponding results are observed for uncovered tanks, with mean slope values 14.91, 14.55 and 15.23 for greenhouse areas 1000, 5000 and 10,000 m^2, respectively (Figure 8). The $\log V_{tank}$ values in all diagrams have been derived from V_{tank} values in m^3.

The aforementioned diagrams might be a useful tool for the prediction of other $Re(\log V_{tank})$ relationships on Crete Island since the ones presented are practically parallel and the space among them is an analogue to their annual rainfall difference. Thus, it is logical to assume that any other station's $Re(\log V_{tank})$ relationship lies somewhere between, depending on the annual rainfall depth.

4. Conclusions

The rainwater tank capacity for meeting the irrigation needs of a tomato crop during an 8-month growing season in a greenhouse is greatly influenced by the rainfall regime of the area where the rainwater harvesting system is located. Both the annual rainfall depth and the longest annual dry period are the major factors that affect rainwater tank sizing.

In the study area with high annual rainfall depth and a moderate dry period, the greatest reliability values on meeting the water needs and the smallest tank capacities were observed. Amongst the study areas with low annual rainfall depth and long dry periods, the greater rainfall depth led to greater reliability values for the rainwater tank, while the larger longest annual dry period led to greater covered rainwater tank capacities for fully meeting the irrigation needs or greater critical tank capacities in the case of uncovered tanks.

Between covered and uncovered tanks of the rainwater harvesting systems, the proper management of stored rainwater is attained by covered tanks with greater reliability values, even reaching 100% with a suitable tank capacity.

Specifically, for covered tanks, a tank size of 200 to 276 m^3 per 1000 m^2 of greenhouse area was adequate for 100% reliability in areas with high mean annual rainfall depth (974.24 mm) and moderate mean longest dry period (87.67 days), and relatively low mean annual rainfall depth (524.12 mm) and high mean longest dry period (117.42 days), respectively.

For uncovered tanks, only a tank size of 520 m^3 per 1000 m^2 of greenhouse area could reach a 100% reliability value in areas with high mean annual rainfall depth and moderate mean longest dry period.

Overall, in all areas examined, a tank (either covered or uncovered) of 30 to 100 m^3 per 1000 m^2 of greenhouse area could reach approximately 80 to 90% reliability, respectively. This is of great practical importance for deciding the economically proper tank size. Detailed benefit–cost issues on this matter could be the subject of a subsequent study.

Finally, the relationship $Re(\log V_{tank})$ was found to be linear for all areas studied. Moreover, these lines were practically parallel and seemed to space analogically to their difference in rainfall depth. This pattern could be investigated in future research for other demand and supply scenarios.

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