Rainwater harvesting tanks' efficiency in Thera Island

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Abstract. The gradual degradation of fresh water reserves, coupled with its essential role in supporting life, is prompting the research for alternative and sustainable methods of supplying water for domestic, irrigation and industrial use worldwide. The harvesting, storage and use of rainwater have been traditionally employed as a water management practice that yields both financial and environmental benefits. In this work, a model of daily water balance has been applied to investigate the efficiency of rainwater harvesting tanks (cisterns) for domestic use on the island of Thera. The amount of rainwater that can be collected from different collection surfaces has been analyzed, in relation with water demand. In addition, the basic parts making up a system for collecting and storing rainwater are considered. These data have been used for the design, costing and optimization of the relevant magnitudes affecting rainwater harvesting systems.

Keywords: rainwater, harvesting, domestic use, Thera Island

1. Introduction

In many countries all over the world, including Greece, water inadequacy is a major problem, in terms of geographical and seasonal distribution of availability and in relation to the local needs. Different techniques and local Rain Water Harvest systems (RWHS) have been developed, countering water scarcity. These RWH systems, i.e. a variety of techniques for the exploitation of rainfall, have durability in time, adaptability to distinct hydrological and climatic conditions, and compatibility with the water resources sustainable management.

Rainwater harvesting systems for domestic use are one of the most promising alternative water supply solutions against the increasing water demand and scarsity. These systems provide water for various uses in a household, and, under the proper treatment, this can be drinkable. Nowadays, they are implemented in different regions around the world (e.g., Brazil (Ghisi *et al.*, 2009), Greece (Sazakli *et al.*, 2007), U.S.A. (Jones and Hunt, 2010), Spain (Domènech and Saurí, 2011)).

Sizing such a system is an issue under investigation, even today. Several methodologies have been proposed for the determination of the optimal size of rainharvesting tanks. These are either behavioral models, and they are based on a daily water balance model (e.g., Imteaz *et al.*, 2011; Ward *et al.*, 2010; Tsihrintzis and Baltas, 2013), or probabilistic models, which are linked to stochastic rainfall generations (e.g., Basinger *et al.*, 2010; Chang *et al.*, 2011). The first category provides measurements for several variables (volumes of consumed and overflowed rainwater, percentage of days in which rainwater demand is met, etc.). However, as the simulation is based on a mass balance equation, a kind of uncertainty to the results is imposed, when using different rainfall data for a specific region. This is partly avoided when long-term rainfall time series are available. On the contrary, although probabilistic methods are robust, it is doubtful if they can describe equally well the rainfall process in one location in comparison to another one (Basinger *et al.*, 2010).

In this research work, the efficiency of a rainwater harvesting system for domestic water use covering is investigated. The implimentation concerns the island of Thera or *Santorini* (Fig.1), which is located in the Southern Aegean Sea and belongs to the Cyclades islands complex. Thera is characterized by particulary low annual precipitation depth (about 300 mm) and a very long arid period (about 5 months). Water consumption in the island is about 708050 m^3 per year; however demand varies significantly during the year, due to the seasonal visitors. Thera is a popular tourist destination (indicatevely, about 366000 tourists in 2015) with a systematically increasing number of visitors, so the problem of water inadequacy is prolonged. According to the available data of the Water Supply and Sewerage Company of Thera (DEYA), in summer months, water consumption doubled in the majority of villages, while in some villages it is three or five times larger. Also, characteristic is the difference in maximum daily water demand during the winter months (50 m^3/d in Akrotiri) and summer (1960 m^3/d in Episkopi, Kamari).

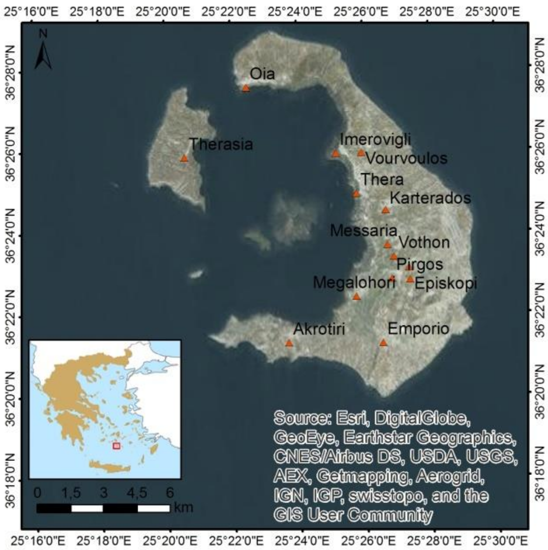


Figure 1. Thera island

Although the allocated amount of water from DEYA has increased in 2006 to 1093828 m^3, there are still shortcomings in the system during peak periods. According to the Management Plan for the Aegean Islands region (2015), the available water resources from the desalination plants and municipal boreholes and wells are not sufficient to cover the water needs, with an annual deficit of 164074 m^3 (in 2012). It is worthy to note that a small amount of this demand (~15000 m^3) is covered by water transportation by ship from continental Greece (Lavrion) to Thera, which imposes a significant cost to the state (12 €/m^3, personal communication with the Water Supply and Sewerage Company). Pricing for the consumers ranges between 1.2 and 3 €/m^3, as the price depends on the accumulated amount and the source of water.

Concerning the permanent consumers in Thera, according to the census of 2011, the number of households is 5862, corresponding to a population of 15171. The 29.02% of the households are composed from two members, the 23.95% from one, the 21.44% from three, 18.05% from four, 5.60% from five and 1.94% from more members. Additionally, regarding houses, it should be mentioned that although the old structures are “cave houses”, the new one tend to be built aboveground with a reinforced concrete roof of smaller or equal to 100 m^2 areas. In combination with the census data, one can assume that an average area of 30 m^2 corresponds to each consumer; an information that is taken into account for the examined scenarios.

To determine the optimal size of rainwater harvesting tank, two RWH methods are performed, which are based on (i) the daily water balance model and (ii) the dry period demand method. The level of the system efficiency is also examined, taking into account, among others, the number of household members (scenarios between 2-5 members), the percentage use of rainwater (3-100%) and the collection area (60-500 m^2) for different tank volumes (≤100 m^3). Finally, the annual financial profit for both the consumers and the state is estimated.

2. Methodological framework

The operation of a domestic rainwater harvesting system is essentially described by a daily water balance model which simulates the procedures of collection and storage of rainwater on a daily basis. For the current purpose, a typical domestic RWHS is considered, consisting of a roof or other available surfaces for the water collection, and a storage tank. This system aims at covering daily water demand, which refers to domestic use except for drinking, and in this context, different percentages of requirements’ fulfillment are examined. Moreover, different collecting surfaces, which is translated in different number of household members (30 m^2/person), as well as, different daily water demands are examined in the model simulation. In the frame of this study, a rainwater harvesting tank balance model (Tsihrintzis and Baltas, 2013; Londra *et al*. 2015) was used for the sizing of rainwater harvesting tank. This method is based on a simple model which requires continuous precipitation timeseries, in order to determine the water volume which may be harvested. This volume defines the capacity of the system’s tank for a given reliability. The general operational principals and equations of the model are described in detail in Londra *et al*. (2015). Any assumptions concerning the first flush (0.33 mm), the runoff coefficient (0.9), the upper-lower limits of the sizing parameters (collective surfaces, tank’s volume, water demand, household’s members, etc.) are also required. For this implementation, daily rainfall data from the meteorological station of Thera for a period of 22 years (1990-2012) were used.

On the contrary, rainwater harvesting tanks sizing using the demand side approach alternative method is a quiet simpler method, than the above mentioned, as well as, widely used. The volume of rainwater harvesting tanks is determined so as to meet the demand for the longest annual average dry season. According to this method, the tank size, $V_{tank,dd}$ is calculated as follows:

$$V_{tank,dd} = N_{dd} \cdot N_{cap} \cdot q \cdot (p/100)$$

where, N_{dd} is the number of dry days, N_{cap} is the number of residents, q is the daily water use per capita (m^3), and p is the percentage of total water demand satisfied by harvested rainwater. N_{dd} is equal to either the maximum ($N_{dd,max}$) or the mean N_{dd} values of the longest annual dry period recorded. Dry period is defined as the period without any rainfall or effective rainfall less or equal to 0.1 mm. In this work, the following scenarios are examined, for daily water demand (q) between 100 and 200 l/cap/day: (i) A two-person household with a collection area equal to 60 m^2 (ii) A three-person household with a collection area equal to 90 m^2 (iii) A four-person household with a collection area equal to 120 m^2 (iv) A five-person household with a collection area equal to 150 m^2. Only the results concerning the first scenario are presented in detail. Concerning the level of the system reliability that enables the determination of the RWHS efficiency for the examined demand levels, the reliability coefficient (*Re*) is calculated, as the percentage of the number of days when demand is completely covered by the available stored water in the tank (*days without tap use*), divided by the total timeseries' timespan.

3. Results and discussion

3.1 Rainwater harvesting tanks sizing using the daily water balance model

This section presents in detail results concerning scenario '1', which refers to two serviced atoms (N_{CAP}=2) with a collecting area A=60 m^2, as this scenario refers to the highest reliability. Daily consumption, *q*, ranges between 100 and 200 l/cap/day, the percentage of total water demand (p) from 3% to 100%, while the tank volumes, V_{tank}, from 5 to 50 m^3, given that the tank is full the first day of the simulation. The stored water volume at each time step of the simulation is presented in Figure 2. The 22-year daily simulation shows that for fresh water requirements equal to 90 l/day (30% of total water needs), the system's efficiency is 51.9%. In the remaining 3861 days, both tank and tap water was used for this percentage of demand.

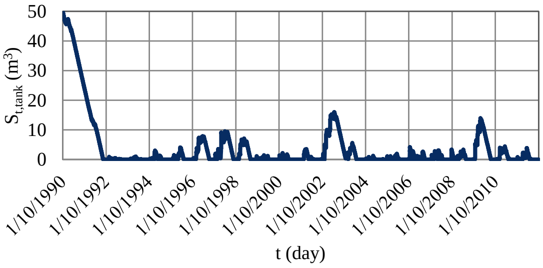


Figure 2. Volume of stored water in the system (scenario 1 for N_{cap}=2, *q*=150 l/cap/day, *A*=60 m^2, V_{tank}=50 m^3, and *p*=30% throughout the simulation

Figure 3 shows the distribution of tap water use for the 30% of demand fulfillment. In 22 years of model simulation, the total volume of harvesting tank water used is 366.7 m^3, while the volume of tap water is 339.3 m^3.

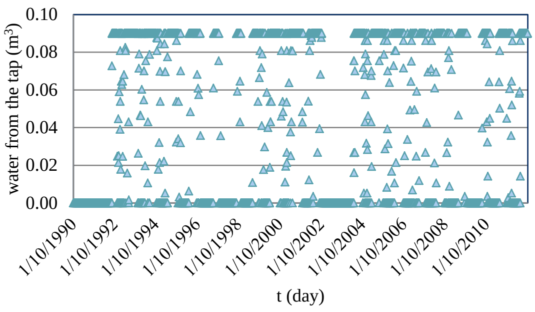


Figure 3. Water volume from the dap (scenario '1', daily model, *p*=30%)

The average annual benefit for a household is estimated as 109 € for an average annual water volume of 16.67 m^3, which means a 15% reduction in the annual cost. The profit for the Water Supply and Sewerage Company of Thera refers to the profit provided by not producing water from desalination or water transportation, i.e., 33 €/year. Then the required tank volume, V_{tank}, for no use of water from the tap is estimated. For *p* between 3% and 10%, tank volumes considered as realistic (also see Tab.1), while for higher levels of requirement tank volumes increase excessively. Indicatively, it is mentioned that the minimum required initial volume of water in the tank is 0.3 m^3 (for p=3% and V_{tank}=2.6 m^3) and 17.5 m^3 (for p=10% and V_{tank}=20.3 m^3). Furthermore, the system performance is investigated, as a function of the tank volume and the percentage of total demand fulfillment. System appears *Re*=100% for *p*=3% and acceptable efficiency for percentage use *p* up to 10%. For *p* greater than or equal to 50%, the efficiency according to the less demanding scenario (*q*=100 l/cap/day with a large storage volume V_{tank}=50 m^3) reaches 50%, while in case of high *q* (e.g., 200 l/cap/day) it is lower than 10%.

Table 1. Rainwater harvesting tank volume for complete fulfillment of demand *p*

p (%)	V_{tank} (m^3)		
	q=100 (L/cap/day)	q=150 (L/cap/day)	q=200 (L/cap/day)
3%	1.6	2.6	3.6
10%	8.5	20.3	37.5
30%	148.4	389.3	630.2
50%	469.7	871.1	1274.2
70%	791.2	1352.0	1915.9
100%	1273.3	2073.6	2877.5

In Figure 4 one can observe the system's efficiency (in terms of *Re*) as a function of the tank volume, for different water demand percentages and for a household of 2 residents (i.e., a collecting area equal to 60 m^2). Regarding the optimum rate of water drained from the tank in relation to the tank capacity and for collection surfaces of 100, 150 and 200 m^2, Figure 5 depicts the results.

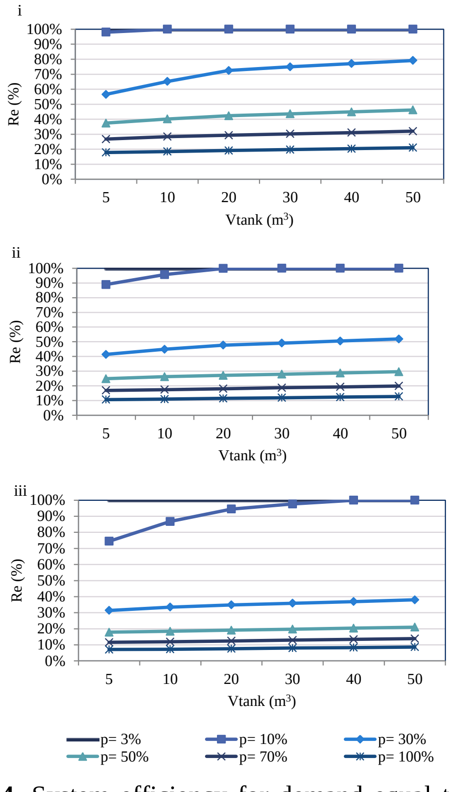


Figure 4. System efficiency for demand equal to (i) 100 l/cap/day, (ii) 150 l/cap/day, (iii) 200 l/cap/day

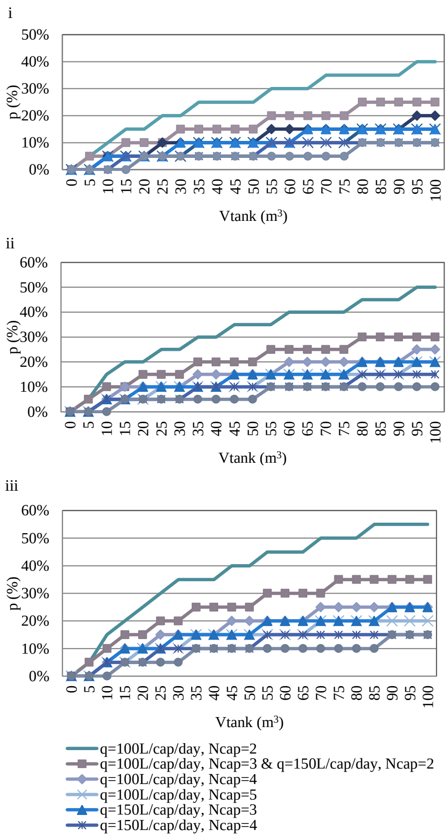


Figure 5. Optimum (*Re*=100%) rate of rainwater use, *p*, as a function of the tank volume, V_{tank}, daily consumption, *q*, number of household members, N_{cap}, for surface (i) *A*=100 m^2, (ii) *A*=150 m^2,, (iii) *A*=200 m^2

3.2 Rainwater harvesting tanks sizing using the demand side approach (dry season demand versus supply

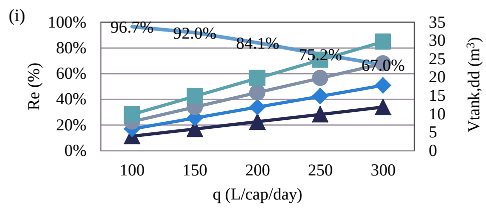
According to the method of maximum dry period (it is noted that dry season in Thera is estimated as 198 days), the required tank volume, $V_{tank,dd}$, for various percentages of use, *p*, daily consumptions, *q*, and numbers of household members, N_{cap}, are presented in Table 2.

Table 2. $V_{tank,dd}$ for the examined scenarios

N_{cap}	p (%)	$V_{tank,dd}$ (m^3)				
		q=100	q=150	q=200	q=250	q=300
2	10	3,96	5,94	7,92	9,90	11,88
3		5,94	8,91	11,88	14,85	17,82
4		7,92	11,88	15,84	19,80	23,76
5		9,90	14,85	19,80	24,75	29,70
2	30	11,88	17,82	23,76	29,70	35,64
3		17,82	26,73	35,64	44,55	53,46
4		23,76	35,64	47,52	59,40	71,28
5		29,70	44,55	59,40	74,25	89,10
2	50	19,80	29,70	39,60	49,50	59,40
3		29,70	44,55	59,40	74,25	89,1
4		39,60	59,40	79,20	99,00	118,80
5		49,50	74,25	99,00	123,75	148,50
2	100	39,60	59,40	79,20	99,00	118,8
3		59,40	89,10	118,80	148,5	178,20
4		79,20	118,80	158,40	198,00	237,60
5		99,00	148,50	198,00	247,50	297,00

As expected, volumes increase when the number of persons, and/or the daily consumption, and/or the percent of tank water use is/are increased. Given the volumes calculated by the method of maximum dry season, $V_{tank,dd}$, and by using them as reference volumes, the daily water balance model was implemented and the system reliability rates for these volumes are calculated. As initial volume, full tank is selected. According to this procedure, it was found that the system's efficiency ranges from 96.7% to 67% for *p*=10% and consumption between 100 and 300 l/cap/day, respectively, whereas for use, *p*, of 100%, it is dramatically reduced; the corresponding amounts range from 20.4% to 6%. For the same daily consumption, *q*, for all four scenarios (regardless the volume calculated by the second method), the system's reliability is the same. Furthermore, the system efficiency was investigated, for different daily consumptions and tank volumes as calculated according to this method ($V_{tank,dd}$). Figure 6 summarizes the findings for the four examined scenarios and for percentages of demand's fulfillment between 10% and 100%. In cases where the system fully meets the water needs of a household, the profitability rates, as expected, are very low in all examined scenarios. Indicatively, *Re*=6% for *q*=600 l/cap/day (Fig. 6.iv).

Finally, the system efficiency also investigated as a function of the percentage of demand fulfillment for *q*=150 l/cap/day. Results show that, by increasing the use rate *p* from 10% to 100%, the system loses 78.9% of its efficiency, which means *Re*=13.1% (not shown).



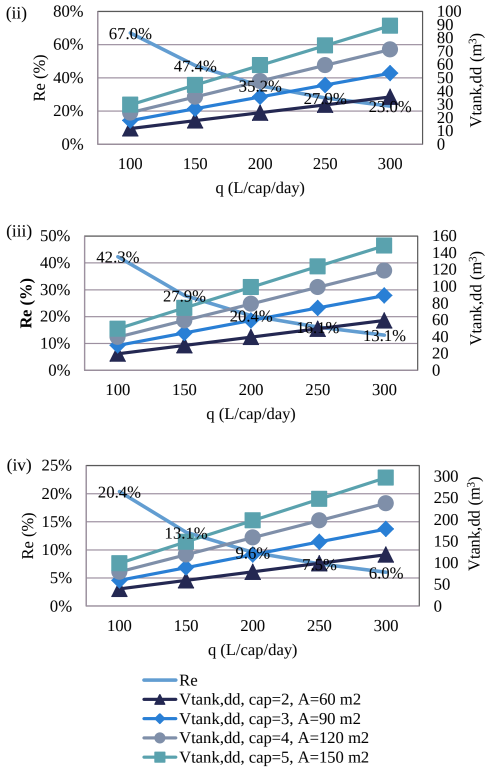


Figure 6. System's reliability for: (i) *p*=10%, (ii) *p*=30%, (iii) *p*=50%, and (iv) *p*=100%.

4. Conclusions

In this paper, the efficiency of a RWHS in Thera is investigated. The system generally presents low level of reliability for average and high percentages of demand fulfillment, due to the combination of low rainfall depth and long dry season. As expected, it was found that the efficiency increases when the percentage of demand for water from the tank decreases or when the tank volume, for a given collection surface, increases. Satisfactory reliability (*Re*>75%) appears when use of tank water is up to 10%. The reliability increases but not noticeably, for greater tank volumes. For utilization levels above 50%, efficiency reaches 50% (about 37 to 46% for capacity of 5 to 50 m^3, respectively) even in the most favorable scenario (with daily consumption of 100 l/cap/day and large storage volume), while, for a daily consumption of 200 l/cap/day receives values from 18 to 21% approximately. In case of 100% level of fulfillment and for high daily consumption (200 l/cap/day), Re is under 10% even for large tank volume. Finally, concerning sizing based on the method of maximum dry season, for average daily consumption of 150 l/cap/day and 10% rate of tank water utilization, the reliability is satisfactory (*Re*~92%), while by increasing the tank water use, efficiency is greatly reduced, reaching 13.1% for all study scenarios in case of exclusive use of tank instead of tap water.

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