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Uncertainty analysis in sizing rainwater harvesting tanks in an isolated island with limited water resources

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Abstract

This research work focuses on the analysis of the involved uncertainty and the corresponding reliability in the sizing of rainwater harvesting systems. For this reason, an uncertainty analysis was carried out, based on 23 years of historic daily record of a station in Kimolos Island (Aegean, Greece). In order to produce the synthetic daily timeseries, a disaggregation procedure was followed. The resulting dataset was used in a rainwater harvesting tank balance model for the optimal sizing of the system. Three representative timeseries, as well as the historic one, were selected for further investigation, concerning two different scenarios. The results show that a rainwater harvesting system in the island of Kimolos does not show great reliability for small collection surface areas. For high reliability, relatively large water collection areas and lower daily water consumptions are required. A cost-benefit analysis was also conducted, which shows that a rainwater harvesting system is advantageous considering the state's expenses for water transportation, but it is profitless for households, based on current pricing of water.

Keywords: Uncertainty analysis, rainfall disaggregation, rainwater harvesting tanks, cost-benefit analysis.

1. Introduction

Water resources engineering deals with the occurrence of water in various parts of a hydrosystem. Hydrological events display variations in time and space; as a result, their occurrences and intensities cannot be predicted precisely in advance, which indicates hydrological uncertainty. The use of a finite record period of rainfall data introduces uncertainty due to sampling error in the estimated rainfall quantiles (Dialynas, 2011). In order to face hydrological uncertainty, several techniques have been proposed to conduct uncertainty analysis. A common and helpful technique is to use stochastic simulation tools to extend the historical date or generate synthetic data with statistical properties similar to those of the observed ones. Moreover, the use of synthetic timeseries instead of a historical data set is essential for providing sufficiently large samples (e.g., greater than the historical series) or ensembles of different timeseries of the same process, in order to evaluate a wide range of possible outcomes (Mimikou *et al.*, 2016). Probabilistic assessment through stochastic simulation is of high importance for all typical water-related problems, since a major objective in the optimal planning and management of hydrosystems is the maximization of the system reliability. For instance, a water-related project is the design of a rainwater harvesting system, as presented herein. Stochastic models have been used for rainfall data generation in the design of rainwater harvesting systems or for other purposes by various scientists (e.g. Lee *et al.*, 2000; Tsubo *et al.*, 2005; Guo and Baetz, 2007; Cowden *et al.*, 2008; Su *et al.*, 2009; Basinger *et al.*, 2010; Chang *et al.*, 2011; Wang and Blackmore, 2012).

Rainwater harvesting, as a water management practice, is widespread all over the world (Valdez *et al.*, 2016) and has been used for over 4.000 years, providing potable and non-potable water for domestic uses, as well as water for agricultural uses (Londra *et al.*, 2015). Rainwater harvesting, based on advanced technology and knowledge, is used even more as a modern, relatively inexpensive and simple water-saving method, and a sustainable water management practice with benefits in reducing stormwater runoff and peaks, and even non-point source pollution (Tsihrintzis and Baltas, 2014). Untreated harvested rainwater can be used for non-potable uses, such as toilet flushing, cloth washing, garden irrigation (Melidis *et al.*, 2007; Gikas and Tsihrintzis, 2012; 2017; Taffere *et al.*, 2016), while, after appropriate treatment, it can be also used as potable water. However, the capacity of rainwater harvesting tanks cannot be formulated, as it is strongly affected by various local variables, such as local rainfall, collection surfaces, demand, and number of served residents, among others (Aladenola and Adeboye, 2010; Eroksuz and Rahman, 2010; Ghisi, 2010; Palla *et al.*, 2012; Londra *et al.*, 2015). Furthermore, methods for sizing the rainwater harvesting tank vary and depend on standards and regulations adopted by each country (Tsihrintzis and Baltas, 2013, 2014; Londra *et al.*, 2015; Gwenzi *et al.*, 2014).

The aim of this research work is the uncertainty analysis in the design of a rainwater harvesting system, in order to investigate reliability. As an application, historical daily rainfall timeseries of the island of Kimolos in Greece and a suitable stochastic model for random number generation are used.

2. Study area - data used

Kimolos Island belongs to the Cyclades island group in the Aegean Sea, Greece (Figure 1). Kimolos faces a significant problem of water shortage, similar to the rest of Cyclades islands. Its normal population is 910 people, which increases by 400-500% in the summer months as a result of tourism. As the area suffers from deficits of water resources and absence of alternative sources of water (e.g., groundwater), this island was selected for the investigation of the reliability of a rainwater harvesting system to store water for toilet flushing and laundry facilities. The scarcity of water resources in Kimolos is a result of climatic conditions, geological structure and its small surface, factors that do not allow the existence of large aquifers. Water demand is covered by water transportation by ship from Lavrion (Attiki), which imposes a significant cost to the state (12 €/m^3; personal communication with the Water Supply and Sewerage Company). Also, due to delays of water transportation resulting from weather or other conditions, residents of the island are faced with water shortages throughout the year. For all these reasons, there is great interest to investigate Kimolos, in order to test how a rainwater harvesting system can solve or minimize the deficit of water, especially during the summer months.

Figure 1. Location of the study area

Since Kimolos does not have a meteorological station, daily rainfall data in the period 1990-2012 (Figure 2) were obtained from the meteorological station in adjacent Milos Island. This meteorological station was chosen as the closest one to Kimolos Island (the horizontal distance is about 2.5 km). The dataset included daily rainfall data for a 23-year period, which was deemed adequate for sizing rainwater harvesting tanks, because it exceeds the requirements in rainfall data for rainwater harvesting tank sizing, according to DIN 1989-1 (2002). Figure 2 presents the abovementioned rainfall data for the period 1990-2012. The mean annual precipitation depth is 383 mm and the total number of dry days, i.e., days with daily rainfall depth less or equal to 1 mm, were 7518 days. This indicates a low rainfall regime in Kimolos. The data were used to produce synthetic timeseries and size the rainwater harvesting tank.

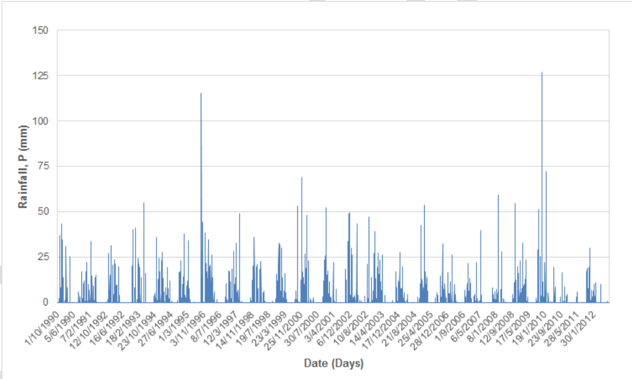

Figure 2. Historical daily rainfall data series from the nearest meteorological station (period: 1990-2012)

3. Methodology

3.1. Sizing of rainwater harvesting tank

A rainwater harvesting tank water balance model (Tsihrintzis and Baltas, 2013, 2014; Londra *et al.*, 2015, 2017) was used for the sizing of the rainwater harvesting tank. The water balance equation used was:

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

where: S_t is the stored volume at the end of t day (m^3); S_{t-1} is the stored volume at the beginning of t day (m^3); R_t is the daily harvested (added) rainwater volume at the end of t day (m^3); D_t is the daily water demand at the end of t day (m^3); and V_{tank} the capacity of the rainwater harvesting tank (m^3).

The daily harvested rainwater volume (runoff), R_t (m^3), from a roof collection area is calculated as:

$$R_t = 10^{-3} \cdot C \cdot A \cdot P_{eff.t} \tag{2}$$

where: C is the runoff coefficient; A is the rainwater collection area (m^2); and $P_{eff,t}$ is the daily effective rainfall depth at the end of t day (mm). In this study, the runoff coefficient was assumed equal to 0.9 and the daily effective rainfall equal to the daily rainfall minus the first flush (Gikas and Tsihrintzis, 2012, 2017). Taking into account the suggestions of Yaziz *et al.* (1989) on improving the quality of harvested rainwater by diverting dust, leaves and bird droppings accumulated on the rainwater collection areas (Gikas and Tsihrintzis, 2012; 2017), the first flush is assumed equal to about 0.33 mm.

$$P_{eff,t} = P_t - 0.33 \quad (3)$$

The daily water demand, D_t, of a household is calculated as:

$$D_t = 10^{-3} \cdot N_{cap} \cdot q \cdot \left(p/100 \right) \quad (4)$$

where: N_{cap} is the number of residents (capita); q is the daily water use per capita (in Greece it ranges from 120 L/cap/day to 180 L/cap/day); and p is the percentage of total water use satisfied by harvested rainwater. The maximum value of p depends on mean annual rainfall, rainwater collection area size, number of residents served and use of collected rainwater (as potable or non-potable). In this study, the water demand for non-potable use of a household with a number of capita N_{cap} = 4 was determined, assuming q = 120 and 150 L/cap/day and p equal to 35% (i.e., 168 and 210 L/day, respectively). This percentage corresponds to water use for toilet flushing (~30%) and clothe washing (~5%) (Londra *et al.*, 2015).

Taking into account Eqs. (1) - (4), the daily stored volume of rainwater is calculated as:

$$S_t = S_{t-1} + 10^{-3} \left[C \cdot A \cdot P_{eff,t} - N_{cap} \cdot q \cdot (p/100) \right] \quad (5)$$

The daily difference between runoff (inflow) and demand (outflow) is calculated using Eqs. (2) and (4), as follows:

$$\Delta S_t = 10^{-3} \left[C \cdot A \cdot P_{eff,t} - N_{cap} \cdot q \cdot (p/100) \right] \quad (6)$$

Consequently, Eq. (5) can be rewritten as:

$$S_t = S_{t-1} + \Delta S_t \quad (7)$$

The calculation of the tank size is iterative and starts from an initial stored water volume $S_{t-1} = S_0$ at time t = 0, which can vary between S_0 = 0 (for initially empty rainwater tank, most conservative) and $S_0 = V_{tank}$ (for initially full rainwater tank).

To take into account the capacity of rainwater tank, V_{tank}, when calculating the daily stored water in the tank, the following heuristic algorithm can be used iteratively:

$$\begin{aligned} &\text{if} \left(S_{t-1} + \Delta S_t \right) > V_{tank} \quad \text{then } S_{t,tank} = V_{tank}, \\ &\text{if} \left(S_{t-1} + \Delta S_t \right) < V_{tank} \quad \text{then } 0, \\ &\text{else } S_t = S_{t,tank} = S_{t-1} + \Delta S_t \end{aligned} \quad (8)$$

where: $S_{t,tank}$ is the actual available stored water volume in the tank at day t.

The volume of water that overflows, O_t, from the tank when the tank is full, can be calculated from the following algorithm:

$$\text{if } S_t \geq V_{tank} \quad \text{then } O_t = S_t - V_{tank}, \text{else } O_t = 0 \quad (9)$$

In the case that the stored water volume in the tank, $S_{t,tank}$, is inadequate to meet the demand, D_t, then the demand will be satisfied, in parts or in whole, with water delivered from the public water supply, T_t, that can be calculated as follows:

$$\text{if} (S_t < D_t) \quad \text{then } T_t = D_t - S_{t,tank}, \text{else } T_t = 0 \quad (10)$$

A reliability coefficient (Rc) is calculated as the percentage of days with water supply from the rainwater harvesting tank to the total amount of days of the rainwater timeseries which are used for dimensioning the rainwater harvesting system:

$$Rc = \frac{\sum (\text{days without tap water use})}{\sum (\text{days of total timespan})} \quad (11)$$

3.2. Disaggregation of synthetic monthly to daily timeseries

Generation of monthly synthetic timeseries was done by using the stochastic autoregressive model AR, 1st order. The persistence was tested using autocorrelogram, according to Anderson's Test (Anderson, 1942; Mimikou *et al.*, 2016).

Because of the necessity of daily rainfall data for the rainwater harvesting tank balance model application, a disaggregation method was employed to convert monthly synthetic timeseries to daily. A large variety of disaggregation methods have appeared in the hydrological literature (e.g., Burlando and Rosso, 1996; Menabde *et al.*, 1999; Olsson and Burlando, 2002; Molnar and Burlando, 2005). However, in this research work, disaggregation was done using the daily rainfall distributions of historical record per month. Specifically, the mean number of dry days and the average (%) distribution of daily rainfall per month were calculated from the historical records of rainfall. Taking into account the different distributions per year of the daily rainfall percentages per month, an average percentage of daily rainfall depths was calculated using the 23 histograms. Based on the average number of dry days per month, the lowest rainfall amounts were transformed into zero, representing the dry days, and their total amount was distributed proportionately in wet days. This procedure of disaggregation is also shown in Figure 3.

In order to examine different rainfall cases, three representative daily synthetic timeseries were selected, comparing their statistical parameters to the historical one. Timeseries 'a' is the 'mean' synthetic daily timeseries with a daily and an annual mean value equal to the corresponding historical mean values per month. Timeseries 'b' is the 'minimum' synthetic daily timeseries, with the minimum mean value, and timeseries 'c' is the 'maximum', with the maximum mean value.

3.3. Cost benefit analysis

In order to evaluate the investment of a rainwater harvesting system in Kimolos for both the residents and the state, a cost-benefit analysis was conducted considering the cost of water consumption and transportation, respectively. Table 1 shows the total cost of the investment that will be evaluated.

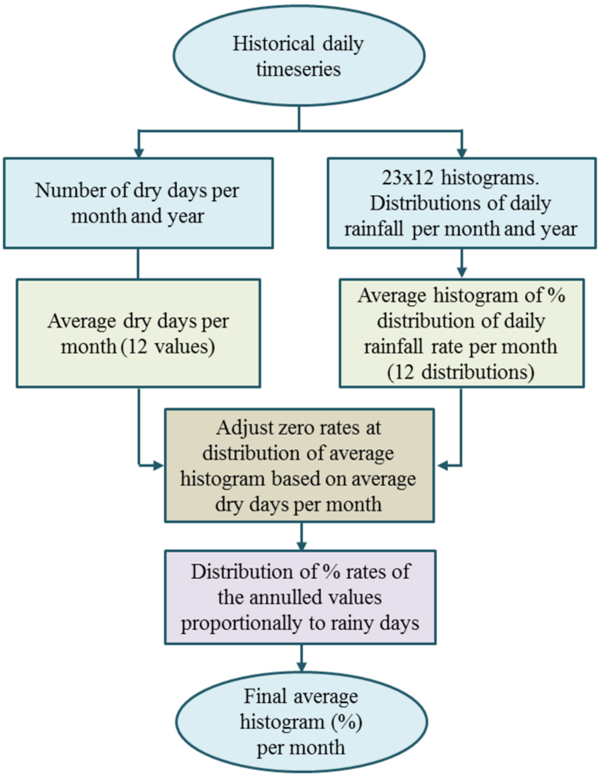

Figure 3. Disaggregation procedures for the generation of daily timeseries

Table 1 Equipment of a rainwater harvesting system and costs

Investment	
Equipment	**Cost, €**
Pump	250
Filters	160
Water distribution system	170
Screening	3
First Flushing Separator	100
Backflow prevention device	120
Tank (Plastic, Cylindrical, Vertical, V = 15 m3, d = 2.7 m, h = 2.7 m)	2800
Total Amount	3603

As mentioned, due to the absence of a local water supply source, water to cover water demand is transported to Kimolos by tankships. The cost of water consumption to residents is 3 €/m^3, while the transportation cost is 12 €/m^3 exclusively for the state. The case that was examined was the most realistic for the island of Kimolos: rainwater tank size V_{tank} = 15 m^3, roof area A = 140 m^2, p = 35%, q = 120 L/capita/day and N_{cap} = 4. Daily draft for a household of 4 people was calculated at 0.17 m^3/day or 61.32 m^3/year. The provided water amount from the rainwater tank was 42 m^3/year and the water amount used from the tap was 20 m^3/year, calculated from the rainwater harvesting tank balance model. Indicatively, if the water amount of the rainwater tank is provided from water transportation, it costs ~126 €/year to residents and ~504 €/year to the state. Additionally, a typical cost of maintenance and operation of 2%/year and discount rates of 3 and 5% were considered. The investment plan was examined for a period of 40 years.

4. Results and discussion

In order to estimate the rainwater harvesting system's reliability, two scenarios (I, II) were investigated using different collection area surfaces, A, ranging between 80 and 300 m^2, and rainwater tank volumes, Vtank, ranging between 5 and 50 m^3, considering the historical daily records (1990-2012) and the three representative synthetic timeseries described above.

According to Scenario I, the rainwater harvesting tank balance model was applied using Ncap = 4, p = 35% and q = 150 L/day/capita and the results are presented in Figure 4. These charts can be used either for sizing new rainwater harvesting systems or for predicting the reliability that existing systems are expected to meet for a given demand, depending on roof area and rainwater tank volume.

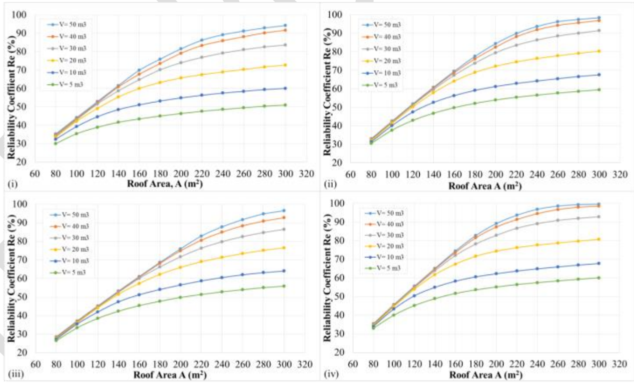

Figure 4. Reliability coefficient for different ranges of roof area and rainwater tank volumes for: (i) the historical record; (ii) the synthetic timeseries 'a'; (iii) the synthetic timeseries 'b'; and (iv) the synthetic timeseries 'c'

A general aspect of all charts is that reliability increases as roof area increases. All timeseries indicate that a reliability of 100% is impossible for a roof area smaller than 300 m^2. The reliability is quite low (Rc<50%) for roof areas between 80 and 120 m^2 and the percentage of total water use is not fully satisfied (35%). From the results, only for timeseries (c), reliability can reach 50% with a roof area of 120 m^2 and rainwater tank volume of 10 m^3. This was expected as timeseries (c) indicates higher average daily rainfall compared to the other timeseries. A reliability of 80% can be succeeded only for large roof areas. For timeseries (a) and the historical record, this amount of reliability requires a roof area A≥200 m^2, and for timeseries (b) and (c) the required roof area is A≥220 m^2 and A≥180 m^2, respectively. A mean reliability 50-60%, can be succeeded by the available roof area A~120-140 m^2 by selecting a certain rainwater tank volume, based on historical record and timeseries (a) results. As timeseries (b) is less favourable and (c) is more advantageous, roof areas A~140-160 m^2 and A~80-100 m^2, respectively, are required to succeed reliability 50-60%. It should be noted that, as these timeseries differ from the historical one, due to the slight difference in their statistical parameters, the present simulation is not suitable for future predictions. In conclusion, concerning timeseries (a) results, a roof area A~160-200 m^2 is required for 80% reliability, while a roof area A~120-140 m^2 is required for 50-60% reliability. In order to have a reliability of 90%, there is need of larger roof areas (240-300 m^2) which are not generally available in the island of Kimolos.

According to Scenario II, the optimal rainwater tank size was investigated depending on desirable reliability (Figures 5 and 6). The tank size of interest is Vtank≤50 m^3, as larger tanks increase cost and take up more space. Roof areas of interest are in the range 120≤A≤300 m^2, daily water use per capita is q = 150 L/capita/day (in case of Scenario IIa: Figure 5) and q = 120 L/capita/day (in case of Scenario IIb: Figure 6), percentage of total water use is p = 35% and the number of consumers per household are Ncap = 4 residents.

Figure 5 shows the tank size for a daily water use per capita 150 L/capita/day (Scenario IIa).

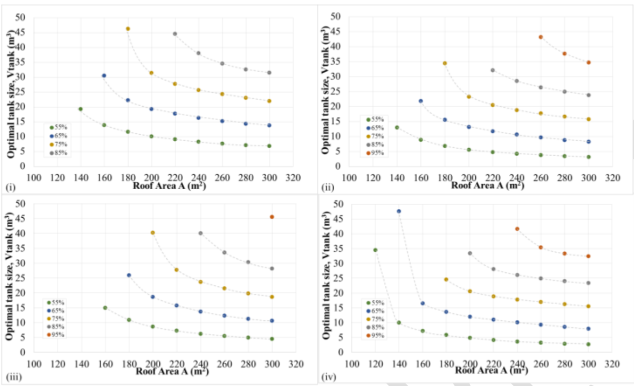

Figure 5. Optimal rainwater tank size for certain reliabilities to meet the percentage of p = 35% of total daily demand for number of capita N_{cap} = 4 and 150 L/capita/day daily water use by using: (i) historical timeseries; (ii) 'a'; (iii) 'b'; and (iv) 'c' synthetic timeseries

Results of synthetic timeseries (a) resemble the results of the historical record. When daily water use per capita is 150 L/capita/day, charts showed the following results. A reliability of 95% requires a rainwater tank of 35-44 m^3 and roof area A≥260 m^2. Consequently, achieving such reliability is only possible by using a large roof area in order to use an acceptable rainwater tank volume less than 50 m3. For reliability of 85%, the required rainwater tank volume of 24-55 m^3 needs to be combined with a roof area A≥220 m^2. To achieve 75% reliability, tank volume of 16-34 m^3 and roof area A≥180 m^2 need to be available. By using rainwater volume tank between 8-22 m^3 and roof area A≥160 m^2, reliability reaches 65%. For reliability of 55%, the required rainwater tank volume should be at least 3-13 m^3 combined with roof area A≥140 m^3.

As the desired reliability decreases, smaller tank volumes are required, so the cost of the system is reduced. If the roof area is larger, smaller tank volumes need to be used for the low rainfall regime of Kimolos Island. Depending on timeseries (b) and (c), results differ from historical record and synthetic timeseries (a) as they indicate lower and higher rainfall regime, respectively. As a result, timeseries (b) indicates that no desired reliability can be succeeded by using roof area less than 160 m2, and even when having available a larger collection area, optimal tank sizes are bigger compared to the results of the historical and synthetic timeseries (a) for the same reliabilities. On the contrary, results for synthetic timeseries (c) show that desired reliabilities can be achieved even for smaller catchment areas, and smaller optimal tank sizes are required for the same reliabilities compared to the rest of timeseries results.

The charts of Figure 7 show optimal tank size for a daily water use of 120 L/capita/day (Scenario IIb). In general, the reduction of daily water use resulted in higher reliabilities by considering the results of all the timeseries. Desired reliabilities are possible to be reached even for small roof areas 120-140 m^2 and smaller tank sizes are required. From the charts, reliability of 95% can be reached even for small roof area combined with smaller volume tank. Specifically, considering timeseries (a), as it simulates better the historical record, for reliability of 95%, the required tank size is 24-48 m^3 combined with roof area A≥200 m^2. For reliability of 85%, the tank size needs to be between 17-43 m^3 with roof area A≥160 m^2. Reliability of 75% can be achieved by using tanks of 11-36 m^3 and roof areas A≥140 m^2. Reliability of 65% requires tank volumes of 5-37 m^3 with available roof areas 120-300 m^2. Finally, for low reliability of 55%, tank volumes of 2-8 m^3 are needed with roof areas A~120-300 m^2.

As a result of cost-benefit analysis, with a discount rate of 3% and considering the cost of water transportation assumed by the state, the investment for all the residents of Kimolos is economically viable with payback period of 20 years, while the payback period with a discount rate of 5% is 28 years. However, as expected, the investment is not viable based on current price of water for residents in case of a private investment, i.e., each household itself financing a domestic rainwater system.

Finally, one has to keep in mind that there are benefits from rainwater harvesting systems not quantified in this analysis, such as relatively good water quality, low carbon footprint and other environmental benefits, and increased supply security and independence.

Regarding future research, further analysis needs to be conducted with the aim of providing different solutions for covering the demand of water in Kimolos and in other islands of Cyclades group which are in similar situation. In Mediterranean islands, such as Kimolos, water demand differs significantly during the year due to the warm summers and the cold winters. As a consequence, a rainwater harvesting model for different daily water use per capita ($q_{summer} \neq q_{winter}$) could be investigated. Furthermore, as the island's population increases in the summer months due to tourism, a different number of residents per household could be considered, depending on season, for sizing more accurate rainwater harvesting tanks. Concerning the stochastic simulation, the use of a different stochastic model would also be of interest, as AR(1) model has the drawback of not maintaining the persistence in the produced timeseries. Finally, another suggestion concerns the disaggregation method applied, where the daily rainfall rate distribution would be investigated, especially in winter months, in order to adjust a theoretical statistical distribution in the rainfall datasets.

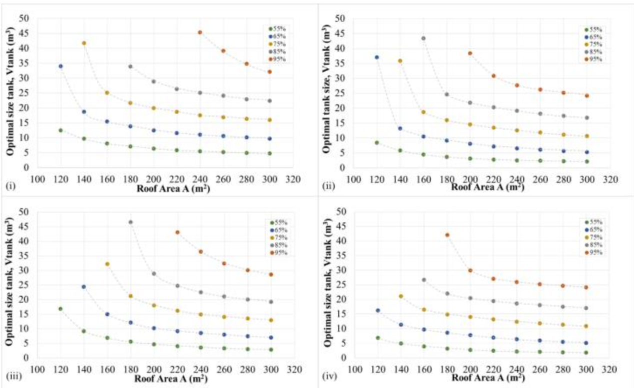

Figure 6. Optimal rainwater tank size for certain reliabilities to meet the percentage of p = 35% of total daily demand for number of capita N_{cap} = 4 and 120 L/capita/day daily water use by using: (i) historical timeseries; (ii) 'a'; (iii) 'b'; and (iv) 'c' synthetic timeseries

5. Conclusions

The main conclusions of this study are the following:

- Synthetic rainfall timeseries were successfully produced using a 23-year daily record.
- Uncertainty analysis in sizing rainwater harvesting systems shows that high reliabilities require presence of large roof areas and low daily water use per capita (q<150 L/capita/day). As there are no large residences with large catchment areas in most isolated islands of the Mediterranean, this leads to medium or low reliabilities (Re≤50%), especially for great daily water use per capita.
- Reduction of daily water use increases reliability and leads to smaller rainwater tank. Daily water use has a huge impact on system's reliability and the volume of rainwater harvesting tank, and must be considered in designing a rainwater harvesting system.
- Cost-benefit analysis reveals a viable investment in a rainwater harvesting system when transportation costs, paid by the state, are considered.

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