

Evaluation of the optimal size of a rainwater harvesting system in Sicily

Vincenza Notaro, Lorena Liuzzo and Gabriele Freni

ABSTRACT

In the Mediterranean area, water scarcity represents a critical issue due to the increasing water demand related to the population growth and the expansion of urban and industrialized areas. Rainwater harvesting (RWH) may be an effective alternative water supply solution to deal with water scarcity in order to reduce non-potable water needs. The reliability of RWH systems is greatly affected by the intensity and the temporal distribution of rainfall events. The purpose of the present study was to identify the optimal tank capacity, in terms of water saving efficiency, of a RWH system installed to supply water for toilet flushing, garden irrigation and both uses with reference to a single-family house in a residential area of Sicily (southern Italy). A water balance simulation of the rainwater storage tank was performed to define the tank release rule. The optimal capacity of the RWH tank was evaluated considering three different catchment surfaces, namely 100, 200 and 300 m². Results showed that, in some areas of the region, the system could be able to provide significant water savings, even with the installation of collecting tanks of less than 10 m³, thus ensuring important environmental and economic benefits to the householders.

Key words | behavioural models, flushing water demand, rainwater harvesting, water balance simulation, water saving efficiency

Vincenza Notaro (corresponding author)
Lorena Liuzzo
Gabriele Freni
Facoltà di Ingegneria ed Architettura,
Università degli Studi di Enna Kore,
Enna,
Italy
E-mail: vincenza.notaro@unikore.it

INTRODUCTION

Many urban areas of the Mediterranean region are affected by scarcity of water resources for domestic use and by the consequences of the intermittent water supply (De Marchis *et al.* 2011, 2013; Fontanazza *et al.* 2013). Moreover, the expansion of urban and industrialized areas will increase the pressure on the available water resources. In the future, climate change will probably intensify this pressure in some parts of the world, including the Mediterranean basin, western United States and southern Africa, producing a further decrease in water resources in the coming decades (Giorgi & Lionello 2008; Hagemann *et al.* 2013). In this context, the development of systems and adaptation measures aimed at the exploitation of alternative water resources has become a critical issue. In particular, the reuse of rainwater is a solution of wide application not

only in arid areas (Yuen *et al.* 2001) but also in densely populated metropolitan urban areas (Deng *et al.* 2013; Schmitter *et al.* 2016).

For a long time, the collection and the use of rainwater for domestic use has been a very common practice in many developing countries. Recently, the practice of rainwater harvesting (RWH) has seen a gradual diffusion in rural areas affected by water scarcity (Abdulla & Al-Shareef 2009; Kahinda *et al.* 2010) and in many urban areas (Liaw & Tsai 2004; Farreny *et al.* 2011) due to its environmental and economic benefits. Several studies have explored the implementation of RWH systems in response to the increasing water demand in Africa (Kahinda *et al.* 2007; Pachpute *et al.* 2009), Asia (Abdulla & Al-Shareef 2009; Jung *et al.* 2014), Australia (Zhang *et al.* 2010; Wang & Blackmore

2012) and Europe (Farreny *et al.* 2011; Campisano & Modica 2012; Liuzzo *et al.* 2016; Notaro *et al.* 2016).

Commonly, RWH systems include three principal components: the catchment area, the collection device and the conveyance system. The catchment area usually consists of rooftops, courtyards or other compacted or treated surfaces. Once rainwater has been intercepted, it can be filtered or subjected to other simple treatments (such as chlorination), then collected in storage tanks to be used. The advantages of RWH systems are numerous:

- depending on the site where they are installed, the rainfall pattern, the used technologies etc., they could require relatively inexpensive technologies that are easy to install and maintain; indeed, RWH systems can be expanded, reconfigured or relocated according to the householders' needs (Worm & van Hattum 2006);
- RWH has significant economic benefits, reducing the amount of water purchased from public systems (Matos *et al.* 2015);
- the availability of an alternative water supply reduces pressure on aquifers and surface waters, providing important environmental benefits (Farreny *et al.* 2011).

Therefore, the integration of RWH systems into residential buildings is an effective way to minimize the use of treated water for non-potable tasks and supply drinking water in places where water is scarce. However, the performance of RWH systems is highly affected by the spatial and temporal distribution of the rainfall in the area of interest. For this reason, RWH by itself is not able to supply water for all domestic uses and make the householders independent from the conventional water supply system. Thus, in order to achieve water self-sufficiency, multiple technologies are needed (Willuweit & O'Sullivan 2013). Nevertheless, the collection and use of rainwater through RWH systems can provide a considerable amount of water and, consequently, significant economic savings to householders. Due to its characteristics, the collected rainwater can be utilized for different non-potable uses, such as toilet flushing, washing machine use and garden irrigation (or any other use that does not require high-quality water). Some studies pointed out the benefits of using harvested rainwater for toilet flushing (Jones *et al.* 2009; Zhang *et al.* 2010).

Many factors affect the performance of a RWH system. In particular the quantity and quality of collected rainwater depends on geographic location, local climate characteristics, presence of anthropic activities in the area and storage tank volume. Thus, the storage capacity of the collecting tank cannot be standardized, but is highly influenced not only by the above-mentioned factors, but also by the characteristics of the catchment surface and the number of householders. Nevertheless an optimal size can be identified on the basis of the system reliability or economic criteria (Liaw & Tsai 2004). Fewkes (1999) carried out some analysis on residential rainwater tanks in the UK, producing a series of dimensionless design curves which allows the estimation of the rainwater tank size required to obtain a desired performance given the roof area and water demand patterns. Khastagir & Jayasuriya (2010) defined a relationship for optimal sizing of rainwater tanks considering the annual rainfall, the water demand, the catchment area and the desired supply reliability valid for the area of Melbourne (Australia). More recently, Notaro *et al.* (2016) provided maps for the identification of the optimal size of a RWH system in Sicily (southern Italy) when the rainwater is intended for toilet flushing use.

In the present study, the reliability of a RWH system for a single-family house in a residential area with four inhabitants has been assessed, considering three different uses of rainwater: toilet flushing, garden irrigation and these two concurrent uses. The system performance has been tested for different catchment surfaces, tank sizes and mean annual precipitation using data from over 100 different sites in Sicily. In order to define a temporal pattern for flushing water demand, water consumption data from single-family houses in Palermo (a coastal city in the northwestern part of Sicily) have been recorded and processed (Fontanazza *et al.* 2016). Water demand for garden irrigation has been estimated based on mean monthly evapotranspiration rates. The application of the Yield-After-Spillage (YAS) algorithm (Jenkins *et al.* 1978; Schiller & Latham 1987) allowed the evaluation of the system efficiency in each site of the region. Simulations have been performed at daily scale using data from 2002 to 2004. Once the system reliability has been assessed, the tank capacities related to three thresholds of reliability (75, 85 and 95%) are determined. Due to the spatial pattern of rainfall, results show a

high degree of variability. For this reason, the spatial distributions of the obtained tank sizes have been reported in some maps, useful for practical applications.

CASE OF STUDY AND DATASET

In the present study rainfall volumes were calculated using the daily rainfall series recorded from 111 rain gauges over the 2002–2004 period in Sicily, one of the 20 administrative regions in Italy. Sicily is an island of approximately 25,700 km² located in southern Italy and characterized by a Mediterranean climate (mild winters and hot, generally dry summers). The total annual rainfall in this region ranges from 400 mm/year at lower elevations to 1,300 mm/year at higher elevations (Figure 1(a)).

The water catchment surfaces of the model home include the home's rooftop and the courtyard. Three

different catchment areas have been investigated: 100, 200 and 300 m². Figure 1(b) shows the analyzed RWH system, in which rainfall (inflow) is collected from the catchment surface and stored in a rainwater tank for toilet flushing and garden irrigation uses (outflow).

For this analysis, rainfall data have been provided by the *Osservatorio delle Acque della Regione Sicilia (Water Observatory of Sicily)*. The 2002–2004 period has been chosen because a large number of homogeneously distributed rain gauges worked continuously during this period. Moreover, these historical rainfall series are representative of the regional climate both in terms of annual and monthly mean values. Indeed, the characteristics of the data recorded during the 2002–2004 period have been compared with those of a longer series (1981–2012). The mean annual rainfall was 724 and 778 mm in the 1981–2012 and 2002–2004 periods, respectively. Table 1 summarizes the total mean monthly rainfall, the mean daily rainfall and the

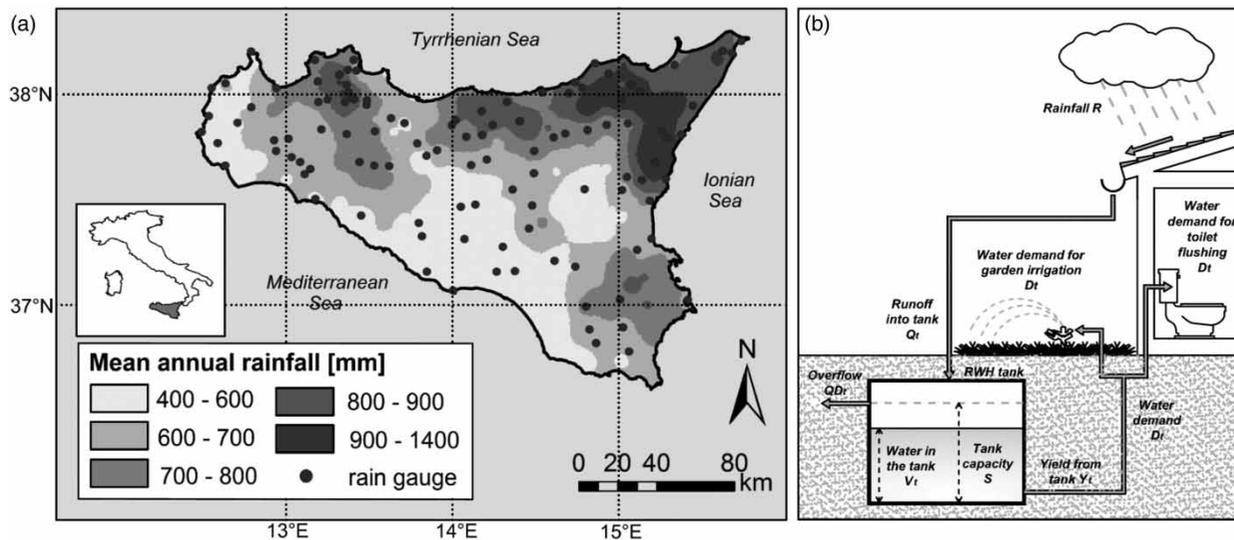


Figure 1 | (a) Spatial distribution of mean annual rainfall for the 1981–2012 period and rain gauges location; (b) scheme of the analyzed RWH system.

Table 1 | Rainfall characteristics with regard to the 1981–2012 period and 2002–2004 periods

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean monthly rainfall [mm/year]	1981–2012	82.8	67.2	60.5	69.4	32.0	20.5	14.3	16.9	77.1	72.7	121.9	143.5
	2002–2004	95.8	76.6	67.8	56.0	26.8	12.5	7.5	15.8	59.6	82.3	90.4	131.9
Mean daily rainfall [mm/day]	1981–2012	7.9	7.3	7.0	6.4	5.6	5.0	5.4	7.1	8.4	9.6	9.0	8.2
	2002–2004	6.3	4.9	5.3	7.3	4.6	5.9	6.3	6.5	7.2	8.4	9.6	10.3
Mean number of rainy days	1981–2012	13	11	10	9	6	3	2	3	6	9	11	14
	2002–2004	14	10	10	11	7	4	2	3	10	9	13	16

mean number of rainy days for each month with regard to the 1981–2012 and 2002–2004 periods.

For the estimation of garden irrigation demand, historical temperature data for the 1981–2012 period have been used, provided by *Osservatorio delle Acque della Regione Sicilia*.

METHODS

Inflow to the RWH tank

The modelled rainwater tank is filled exclusively using rainfall volumes collected from a building's rooftop, courtyard and pedestrian areas. Under the hypothesis of constant rainfall within each time step t , the rainwater volume can be evaluated using the following expression:

$$W_t = \varphi \cdot A_{TOT} \cdot R_t = A \cdot R_t \quad (1)$$

where W_t is the inflow volume supplied to the tank at time step t (m^3), φ is the runoff coefficient depending on water loss (dimensionless), R_t is the rainfall at time t (m), A_{TOT} is the total catchment surface area (m^2), and A is the effective impervious surface area (m^2). In the analysed RWH layout, the tank is installed underground, thus the evaporation losses from the tank can be neglected. In this analysis, φ was set equal to 0.9 (Wisner & P'ng 1983).

Water demand for toilet flushing

The evaluation of the average number of daily flushes per capita could be considered satisfactory to accurately model daily water demand for toilet flushing; nevertheless, these observations may not be universally applicable to all RWH systems. Thus, a precise modelling of water demand patterns for toilet flushing is required.

In this study, the toilet flushing demand pattern was determined by analyzing water consumption data collected during a monitoring campaign of seven dwellings located in Palermo throughout the 2002–2004 period (Fontanazza *et al.* 2016). The monitoring period was long enough to identify weekly, monthly and seasonal toilet flushing patterns. The customers that participated in the consumption

monitoring programme had the following characteristics: families with at least two members with age ranging from 4 to 70 years, negligible outdoor consumption and interest in participating. Each monitored dwelling was equipped with a toilet WC flush tank of 9–10 L (the usual volume for a WC flush tank) and a bowl filling time ranging between 0.95 and 1 minute.

A monitoring apparatus, involving a Class C multi-jet water metre and a data logger, was installed on the service line of each of the seven dwellings downstream of the revenue water metre to monitor domestic water use. The two devices were coupled by means of an impulse sensor. Whenever the cumulative volume consumed reached 0.5 L, the sensor transmitted a signal to the data logger. A common faucet is characterized by flows in the range 6–12 L/min, and the metre was able to disclose consumption pulses longer than or equal to 5 seconds (in the worst case) or equal to 2.5 seconds (in the best case), allowing to separate out toilet flushing data from other uses. In any case, if small pulses were not identifiable, their volume was aggregated into the next consumption pulse.

Once the data were acquired, the number of daily flushing was evaluated for each dwelling and monitoring day according to the procedure proposed by Campisano & Modica (2014). Namely, the water consumption data were filtered to identify data points where use ranged from 9 to 10 L over a period of 1 minute. Knowing the filling time of the WC flush tank was important to exclude consumption data with the same volume but linked to other uses. In the absence of more specific information, the number of daily flushes per capita was then calculated for all monitored days as the number of flushes per day divided by the average number of users present, or the number of family members in each monitored household. Table 2 displays the average number of daily flushes per capita for each monitored dwelling and the related root mean square error (RMSE). Results are similar to those reported in previous studies in literature concerning single-family houses, for which the authors found that the mean number of flushes per person and per day ranged between 5 and 7 (e.g. Campisano & Modica 2014; Lizárraga-Mendiola *et al.* 2015). Lastly, the number of daily flushes per capita were statistically analyzed to identify a well-fitting probability distribution function. Several probability distribution functions were investigated, including the

Table 2 | Results of statistical analysis carried out on water consumption data collected for seven dwellings located in Palermo and monitored during the 2002–2004 period

Dwelling	No. persons	Monitoring days	Average flushings/ (day-capita)	RMSE	CDF	λ	κ	K-S test $D_{0.05}$
1	3	334	5.73	2.925	Weibull	6.66	2.234	0.071
2	4	359	5.77	2.951	Weibull	6.57	2.094	0.068
3	2	317	4.79	2.978	Weibull	5.77	1.912	0.060
4	3	237	4.62	2.974	Weibull	5.34	1.654	0.065
5	2	212	6.46	2.885	Weibull	7.31	2.410	0.077
6	4	637	5.12	2.798	Weibull	5.90	2.020	0.022
7	3	320	4.75	2.980	Weibull	5.35	1.674	0.059

Normal, Poisson, Weibull, Exponential, etc., finding that the Weibull distribution function fit the observed data best. The Kolmogorov–Smirnov statistical test (confidence level equal to 0.05) confirmed this result. Table 2 also shows data for the two parameters λ and κ of the related Weibull distribution function and the results of the Kolmogorov–Smirnov test for each dwelling.

An analysis of the processed data revealed that dwelling six was representative of all monitored dwellings, with an average number of flushes per capita per day equal to 5.12 and a minor RMSE value equal to 2.798. Thus, dwelling six has been chosen in order to define the water demand pattern for toilet flushing in Sicily.

To generalize the results to other similar users, 365 random points were sampled from the Weibull cumulative distribution function fitting the cumulated frequency of the obtained per capita flushes for dwelling six. Thereby, a daily pattern of toilet flushes per capita for an entire year was defined. The series of daily household toilet flushes F_d were obtained by multiplying the number of per capita flushes f_d and the number of users at home during the day N_u :

$$F_d = f_d \cdot N_u \quad (2)$$

Following the approach described by Campisano & Modica (2014), a water demand for toilet flushing at the sub-daily scale could have been evaluated, starting from the daily demand pattern. A sub-daily pattern of water demand for toilet flushing would have allowed investigation of the implications of the peaks in water consumption for toilet flushing on the performance of the RWH system. Nevertheless, in this case, the simulation of the water

balance of the RWH system would have required precipitation data at a sub-daily scale that are not available for all the rain gauges considered in this study. Moreover, this study focused on the performance of the RWH system in terms of average annual water saving efficiency.

Water demand for garden irrigation

The frequency of irrigation depends on many factors, such as the type of grass to be irrigated, the soil properties and the climatic conditions in the area of interest. In order to define the water demand for garden irrigation, it was assumed that the garden area (200 m²) of the modelled single-family house was planted with turfgrass. Therefore, the mean monthly reference evapotranspiration (RE) value was evaluated for the area of study using the Thornthwaite formula (Thornthwaite 1948). Water use for turfgrasses was estimated using a correlation factor, the crop coefficient K_c , as follows:

$$AE = RE \cdot K_c \quad (3)$$

where AE is the actual evapotranspiration in mm/day. Turfgrass K_c values fluctuate slightly during the season based on the percentage of plant cover, growth rate, root growth, stage of plant development and management practices. In this analysis, K_c was set equal to 0.85 (Allen et al. 1998).

Optimum irrigation frequency depends on the geographic location, the plant species, the soil type and the climatic conditions. In this study, the frequency of irrigation was defined based on practical considerations and previous literature (Jordan et al. 2003; Fu & Dernoeden 2009;

Table 3 | Potential and actual evapotranspiration (mm/day) and the irrigation frequency for each month of garden irrigation with harvested rainwater

Month	RE (mm/day)	AE (mm/day)	Irrigation frequency
April	1.5	1.3	Every 3 days
May	2.4	2.0	Every 3 days
June	3.5	3.0	Alternate days
July	4.3	3.7	Alternate days
August	4.5	3.8	Alternate days
September	3.5	3.0	Every 3 days

Marchione 2009). The need for further specific information to define the optimal irrigation frequency for turfgrass required some assumptions to be made in this study. Namely, it was assumed that the garden was planted with *Zoysia Japonica Compadre*, a turfgrass more resistant to warm climates than other species. It was also assumed that the garden was only irrigated every 3 days during April, May and September, and on alternate days from June to August. The potential and actual daily evapotranspiration and the irrigation frequency for each month are reported in Table 3.

Water balance simulation

The performance and design of RWH systems can be investigated using different approaches, including water balance simulation analyses and mass curve analyses (Ghisi et al. 2007), probabilistic methods (Guo & Baetz 2007) and economic optimization (Liaw & Tsai 2004). Simple mass balance approaches based on annual precipitation volumes are usually applied, even if these methodologies do not ensure an adequate level of accuracy in sizing RWH systems. Behavioural models are also commonly used because they allow a more detailed design and are relatively simple to develop. Nevertheless, these models usually underestimate the need for storage tank capacity compared with simple mass balance simulations (Ward et al. 2010).

In a behavioural model, the changes in the storage content of a finite reservoir are computed using the water balance equation. Water fluxes consist of runoff into a tank (inflow), overflow from the tank and the yield extracted from the tank; demand is met in each operating period to the extent that storage is available. The algorithm for the

model relies on a YAS operating rule (Jenkins et al. 1978):

$$W_{D_t} = \max \left\{ \begin{array}{l} V_{t-1} + W_t - S \\ 0 \end{array} \right. \quad (4)$$

$$Y_t = \min \left\{ \begin{array}{l} D_t \\ V_{t-1} \end{array} \right. \quad (5)$$

$$V_t = \min \left\{ \begin{array}{l} V_{t-1} + W_t - Y_t \\ S - Y_t \end{array} \right. \quad (6)$$

where W_{D_t} (m^3) is the volume discharged as overflow from the storage tank at time step t , V_t (m^3) is the volume stored at time step t , Y_t (m^3) is the yield of rainwater from the storage tank at time step t , D_t (m^3) is the toilet and grass irrigation water demand at time step t , and S (m^3) is the tank storage capacity.

Generally, the performance of RWH systems is described in terms of reliability, expressed as the total actual rainwater supply over water demand E_T :

$$E_T = \frac{\sum_{t=1}^T Y_t}{\sum_{t=1}^T D_t} \cdot 100 \quad (7)$$

where T is the total time period under consideration. E_T represents the overall water savings that can be achieved by harvesting and using rainwater.

RESULTS AND DISCUSSION

Evaluation of water saving efficiency at daily scale

The historical rainfall series recorded at 111 rain gauges during the 2002–2004 period have been used to investigate the performance of an RWH system in Sicily. First of all, a preliminary analysis has been carried out to examine the implication of the tank capacity S on the daily E_T and to identify the S able to provide the most feasible value of the average daily E_T for each site in the region of interest. As previously mentioned, three different extents of the surface of interception A (100, 200 and 300 m^2) have been

considered. Simulations were conducted on a daily scale, in order to take into account the effect of extreme rainfall of 24 hours duration and droughts on the system performance.

For each value of the tank capacity in the range 1–30 m³, the average daily value of E_T related to the entire analyzed period has been calculated. The box-whisker graphs in Figure 2 summarized the obtained results. Focusing on the median line (50th percentile), the average daily reliability E_T increases with tank capacity. For S in the range 1–30 m³, E_T varies from 38 to 72% for $A = 100$ m², from 44 to 96% for $A = 200$ m² and from 46 to 99% for $A = 300$ m². Figure 2(a) shows that for $A = 100$ m², a tank capacity equal to 20 m³ is able to provide a water saving efficiency of 70%. Further increases of S produce a slight improvement of E_T , with an achievable maximum value equal to 72%. Likewise the performance improvement of

the RWH system in terms of E_T is moderate and not economically advantageous for tank capacities greater than 20 m³ for A equal to 200 and 300 m² (Figure 2(b) and 2(c)). However, the increase of the catchment surface clearly produces higher values of the maximum achievable E_T . Specifically, a 20 m³ capacity allows E_T values to be obtained close to 100%, when a catchment surface area of 200 m² is available.

In the case of the use of rainwater for garden irrigation (Figure 2(d)–2(f)), the median curve shows how the efficiency of the system depends on the installed tank capacity. However, the achievement of high values of E_T requires capacity greater than 20 m³. For this use, the time shift between water demand for irrigation (higher in the summer months), and the rainy volumes (less in summer) has considerable consequences on the RWH system

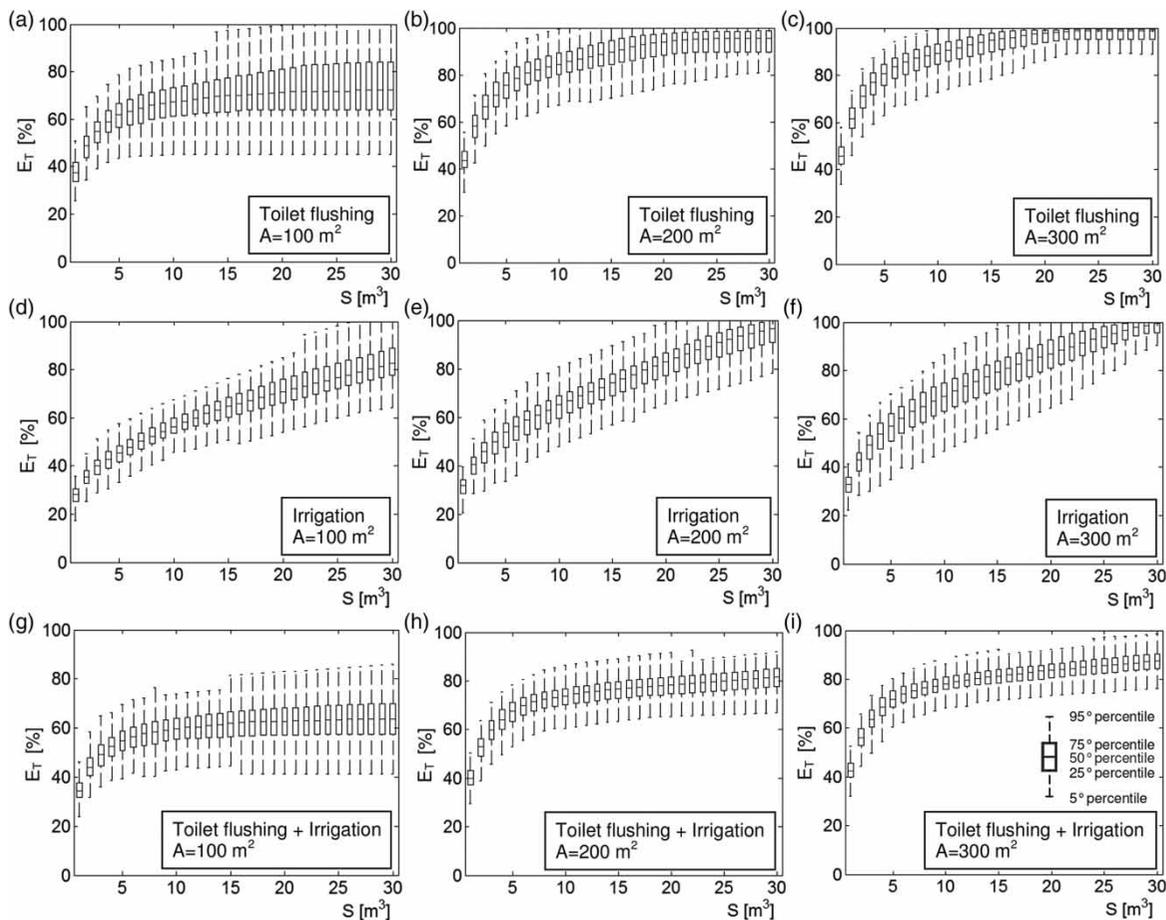


Figure 2 | Box-whisker graphs of the daily water saving efficiency E_T vs tank capacity S for different catchment surface A and different rainwater use.

performance. In this case, greater capacities allow more rainwater to be stored that can be used during the summer months. Even in this case, the availability of greater catchment surfaces improves the efficiency of the system. For S between 1 and 30 m^3 , E_T ranges between 28 and 82% for $A = 100 \text{ m}^2$, between 31 and 96% for $A = 200 \text{ m}^2$ and between 33 and 99% for $A = 300 \text{ m}^2$.

In the case of combined use of rainwater (Figure 2(g)–2(i)) it can be observed that, for a catchment surface A of 100 m^2 , on average, the system allows the achievement of E_T values up to 60%, even for tank capacities greater than 20 m^3 . The increase of the catchment surface implies a slight improvement of the system performance. In particular, for $A = 300 \text{ m}^2$, it is possible to obtain E_T values higher than 80%. However, increases over 20 m^3 do not produce large increases of E_T and therefore they are not economically advantageous. For S between 1 and 30 m^3 , E_T ranges between 34 and 63% for $A = 100 \text{ m}^2$, between 40 and 81% for $A = 200 \text{ m}^2$ and between 42 and 87% for $A = 300 \text{ m}^2$.

Spatial distribution of the optimal capacity of the collection tank

For each rain gauge in Sicily, mean annual E_T related to each value of S (ranging from 1 to 30 m^3) have been evaluated. Subsequently, the tank capacities for which three different thresholds of E_T could be reached, specifically 75, 85 and 95%, have been identified. Maps in Figure 3 show the spatial distribution of E_T when rainwater is used for toilet flushing. For $A = 100 \text{ m}^2$, the system is not able to provide a mean annual E_T equal to 75% in most of the region (Figure 3(a)). In some northern coastal areas this threshold can be reached with a capacity ranging from 2 to 8 m^3 , nevertheless in the remaining part of the island, higher capacities are required. The system provides mean annual E_T equal to 85 and 95% only in a limited area in the northwestern part of the island (Figure 3(b) and 3(c)). However, these thresholds can be reached with tank capacities up to 20 m^3 . For $A = 200 \text{ m}^2$, a mean annual E_T equal to 75% can be obtained in the

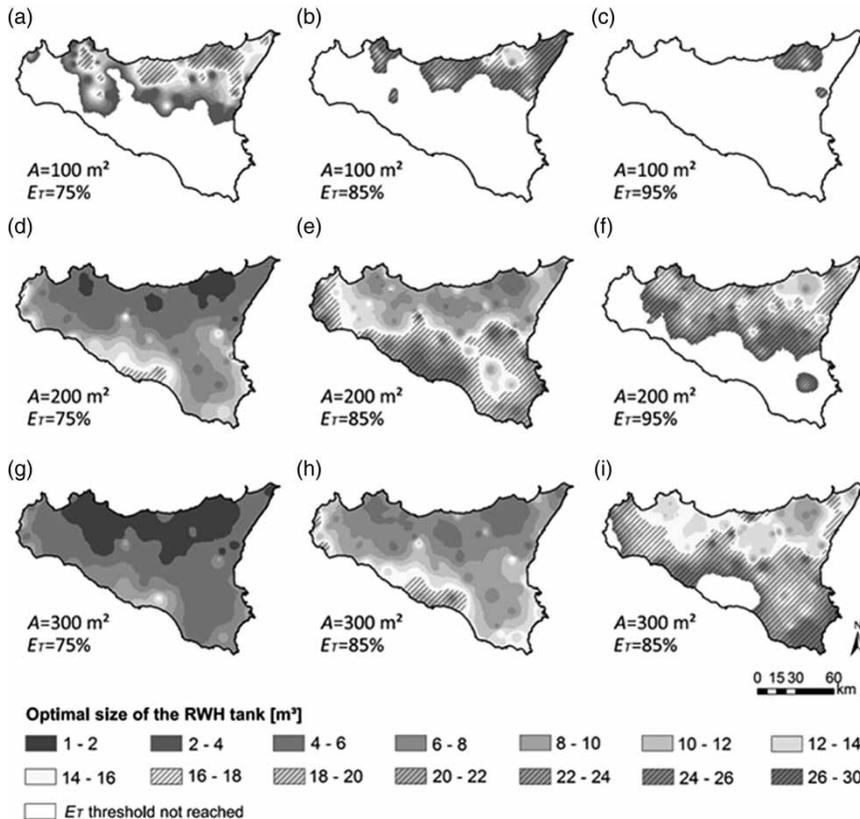


Figure 3 | Optimal tank capacity (m^3) for different E_T threshold (%) and A (m^2) for toilet flushing use.

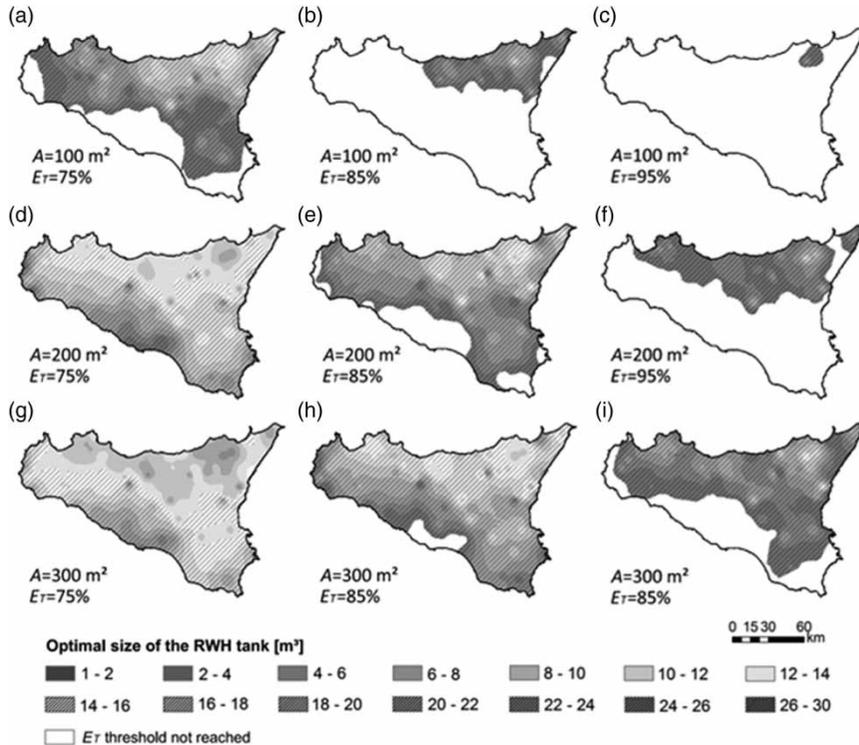


Figure 4 | Optimal tank capacity (m^3) for different E_T threshold (%) and A (m^2) for garden irrigation use.

whole region by the installation of tank with capacities ranging from 1 to 15 m^3 (Figure 3(d)), whereas the achievement of the remaining thresholds requires higher volumes (Figure 3(e) and 3(f)). The system is able to provide an E_T equal to 95% in most of the island, even if the threshold cannot be reached in a wide southern area and a western zone (Figure 3(f)). Figure 3(g) shows that for $A = 300 \text{ m}^2$, the 75% threshold can be obtained in the whole area of study, also using small tank capacities. Specifically, in the northern part of the region, the RWH system can provide mean annual E_T up to 85% by the installation of capacities that range between 6 and 8 m^3 . The 95% threshold can be obtained in the whole region, except for two small areas located in the eastern and southern part of the island (Figure 3(i)).

Figure 4 shows the capacities required for the achievement of the defined threshold of E_T when rainwater is used for garden irrigation. For a catchment surface A equal to 100 m^2 (Figure 4(a)–4(c)), the achievement of the 75% threshold requires the installation of a tank with a capacity of $15\text{--}30 \text{ m}^3$ in almost all Sicily. The failure to achieve the thresholds of 85 and 95% in most of the island

points out that the RWH system, for the considered volumes, is not appropriate for the satisfaction of the water demand for irrigation. In the case of $A = 200 \text{ m}^2$, the RWH system is able to provide a value of average annual E_T equal to 75% in the entire study area (Figure 4(d)), by requiring, in the northern part of the island, lower volumes if compared with the capacity required for the attainment of the threshold in the southern part. For E_T equal to 85%, the system does not meet the water demand in a wide southern area of the island, while in the remaining part tanks with volumes ranging between 15 and 30 m^3 are required. For $A = 300 \text{ m}^2$, E_T reaches 75% across the region (Figure 4(g)), with volumes ranging from 6 to 10 m^3 in the northern part of the island. In order to obtain an E_T equal to 85%, an increase of the tank capacity is required, especially in the southern part of the region (Figure 4(h)). The 95% threshold cannot be obtained in the whole Sicilian territory, and where reachable, requires capacities up to 30 m^3 , which is economically disadvantageous.

It has to be remarked that the assumptions made in order to define the water demand for garden irrigation clearly affected the results shown in the maps of Figure 4.

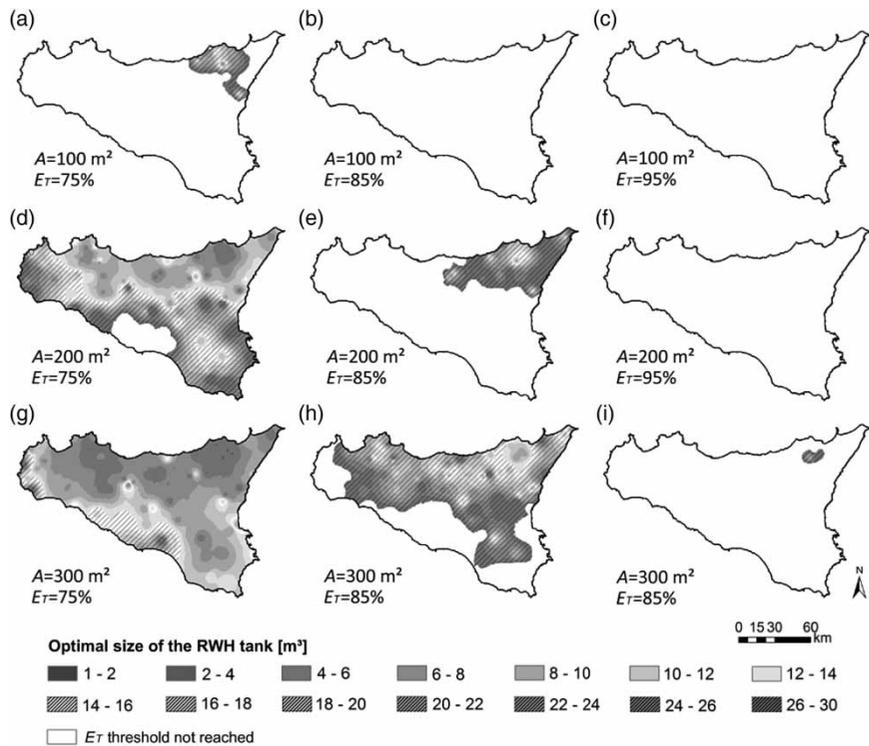


Figure 5 | Optimal tank capacity (m^3) for different E_T threshold (%) and A (m^2) for toilet flushing and garden irrigation uses.

Indeed, if the garden had been planted with less water demanding plants (such as succulent plants), the performance of the system would have been better. On the contrary, the assumption of a garden planted with flowers or fruit trees, that require more frequent irrigation and higher volumes of water, would have provided lower values of water saving efficiency, if compared with the analyzed condition.

Figure 5 displays the capacities required for the achievement of the E_T threshold when the rainwater is used both for toilet flushing and garden irrigation. For $A = 100 \text{ m}^2$, the system is not enough to meet the water demand and obtain an E_T equal to 75% (Figure 5(a)), except for a limited area in the northeast, where mean annual precipitation is higher than the rest of the region. For the two uses of rainwater, mean annual E_T does not reach 85 and 95% in any area of Sicily (Figure 5(b) and 5(c)). Increases of A up to 200 m^2 allow an E_T equal to 75% in most of the island to be obtained (Figure 5(e)), nevertheless the threshold of 95% cannot be reached in any area in this case (Figure 5(f)). The system becomes more efficient when a catchment surface of 300 m^2 is available, reaching an E_T equal to 75% in

most of the region with capacities in the range of $4\text{--}15 \text{ m}^3$ (Figure 5(h)). However, the achievement of the 85% threshold is not possible in the whole region, and, in the cases in which it can be obtained, it requires tank capacities ranging from 20 to 30 m^3 . Figure 5(i) shows that the system is not able to provide an E_T equal to 95%, except for a small area in the northeast.

CONCLUSIONS

For a long time, rainwater collection systems have been an important source of water supply in arid and semi-arid areas of the Mediterranean. Nevertheless, the increasing pressure on water resources, especially related to climate change and the expansion of urban and industrialized areas, has aroused great interest in the possibility to install these systems in urban areas as an alternative water source to be integrated with traditional water supply systems.

In this analysis, a behavioral model was applied in order to investigate the performance of an RWH system in terms of its reliability. Water demand for toilet flushing and

garden irrigation and 3 years of historical daily rainfall data for 111 locations in Sicily were used as input to the system simulation model, the YAS algorithm. Water demand for flushing was calculated as the number of daily flushes per capita, which was obtained by analyzing water consumption data collected during a 2-year measurement campaign in Palermo (northwestern Sicily). Water demand for garden irrigation was evaluated by estimating the mean monthly reference evapotranspiration.

The results highlighted the potential for good performance of the RWH systems in Sicily when the water collected is intended only for toilet flushing. Specifically, a tank capacity equal to 20 m³ is able to ensure the complete satisfaction of water demand in many areas of the region. Conversely, the use for garden irrigation is not economically convenient as in many areas of the island it requires tank capacities greater than 20 m³. Similarly, the installation of RWH systems for both rainwater uses is not advantageous in most of the analyzed sites.

A considerable reduction of the capacity of the RWH tank could be achieved by the installation of WC flush tanks of smaller volumes. For example, considering the 75% threshold of E_T for the solely toilet flushing use, a WC flush tank of 6 L could provide an average reduction of the RWH tank capacity that ranges between 50 and 40%, depending on the catchment surface. This reduction is less significant when the uses for toilet flushing and garden irrigation are concurrent. Specifically, this reduction could range on average between 20 and 30%.

In this analysis some assumptions have been made in order to estimate water demand for garden irrigation. Further developments of this study could include a more accurate estimation of this demand, in terms of temporal pattern and water amount, for example by means of a water balance model.

It has to be remarked that the analysis here proposed is not intended to be exhaustive. Indeed, before installing an RWH system, a cost-benefit analysis needs to be carried out, in order to verify if the achievement of a certain threshold of reliability is not too costly and, therefore, economically disadvantageous. This study can be considered as a preliminary analysis to identify in which areas the installation of an RWH system could provide benefits in terms of water saving efficiency and at which level.

In summary, the study showed that in some areas of Sicily RWH systems, integrated with conventional water supply systems, can provide significant water savings. For this reason, incentives and government support should be promoted in order to encourage householders to install RWH water systems in residential urban areas.

REFERENCES

- Abdulla, F. A. & Al-Shareef, A. W. 2009 [Roof rainwater harvesting systems for household water supply in Jordan](#). *Desalination* **243** (1), 195–207.
- Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998 *Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements*. FAO Irrigation and Drainage Paper 56. FAO, Rome, 300(9), D05109.
- Campisano, A. & Modica, C. 2012 [Optimal sizing of storage tanks for domestic rainwater harvesting in Sicily](#). *Resour. Conserv. Recycl.* **63**, 9–16.
- Campisano, A. & Modica, C. 2014 [Selecting time scale resolution to evaluate water saving and retention potential of rainwater harvesting tanks](#). *Proc. Eng.* **70**, 218–227.
- De Marchis, M., Fontanazza, C. M., Freni, G., La Loggia, G., Napoli, E. & Notaro, V. 2011 [Analysis of the impact of intermittent distribution by modelling the network-filling process](#). *J. Hydroinform.* **13** (3), 358–373.
- De Marchis, M., Fontanazza, C. M., Freni, G., La Loggia, G., Notaro, V. & Puleo, V. 2013 [A mathematical model to evaluate apparent losses due to meter under-registration in intermittent water distribution networks](#). *Water Sci. Technol. Water Supply* **13** (4), 914–923.
- Deng, Y., Cardin, M. A., Babovic, V., Santhanakrishnan, D., Schmitter, P. & Meshgi, A. 2013 [Valuing flexibilities in the design of urban water management systems](#). *Water Res.* **47** (20), 7162–7174.
- Farreny, R., Gabarrell, X. & Rieradevall, J. 2011 [Cost-efficiency of rainwater harvesting strategies in dense Mediterranean neighborhoods](#). *Resour. Conserv. Recycl.* **55** (7), 686–694.
- Fewkes, A. 1999 [The use of rainwater for WC flushing: the field testing of a collection system](#). *Build. Environ.* **34** (6), 765–772.
- Fontanazza, C. M., Freni, G., La Loggia, G., Notaro, V. & Puleo, V. 2013 [Evaluation of the water scarcity energy cost for users](#). *Energies* **6** (1), 220–234.
- Fontanazza, C. M., Notaro, V., Puleo, V. & Freni, G. 2016 [Multivariate statistical analysis for water demand modelling: implementation, performance analysis, and comparison with the PRP model](#). *J. Hydroinform.* **18** (1), 4–22.
- Fu, J. & Dernoeden, P. H. 2009 [Creeping bentgrass putting green turf responses to two irrigation practices: quality, chlorophyll, canopy temperature, and thatch-mat](#). *Crop Sci.* **49** (3), 1071–1078.

- Ghisi, E., Bressan, D. L. & Martini, M. 2007 Rainwater tank capacity and potential for potable water savings by using rainwater in the residential sector of southeastern Brazil. *Build. Environ.* **42** (4), 1654–1666.
- Giorgi, F. & Lionello, P. 2008 Climate change projections for the Mediterranean region. *Glob. Planet. Change* **63** (2), 90–104.
- Guo, Y. & Baetz, B. W. 2007 Sizing of rainwater storage units for green building applications. *J. Hydrol. Eng.* **12** (2), 197–205.
- Hagemann, S., Chen, C., Clark, D., Folwell, S., Gosling, S. N., Haddeland, I. & Wiltshire, A. 2013 Climate change impact on available water resources obtained using multiple global climate and hydrology models. *Earth Syst. Dynam.* **4**, 129–144.
- Jenkins, D., Pearson, F., Moore, E., Sun, J. K. & Valentine, R. 1978 *Feasibility of Rainwater Collection Systems in California*. Contribution No. 173. Californian Water Resources Centre, University of California.
- Jones, M., Hunt, V. F. & Wright, J. 2009 Rainwater harvesting experiences in the humid south-east USA. In: *Proc. of the World Env. and Water Resources Congress*, May 17–21, 2009, Kansas City, Missouri.
- Jordan, J. E., White, R. H., Vietor, D. M., Hale, T. C., Thomas, J. C. & Engelke, M. C. 2003 Effect of irrigation frequency on turf quality, shoot density, and root length density of five bentgrass cultivars. *Crop Sci.* **43** (1), 282–287.
- Jung, K., Lee, T., Choi, B. G. & Hong, S. 2014 Rainwater harvesting system for continuous water supply to the regions with high seasonal rainfall variations. *Water Resour. Manage.* **29**, 1–12.
- Kahinda, J. M. M., Taigbenu, A. E. & Boroto, J. R. 2007 Domestic rainwater harvesting to improve water supply in rural South Africa. *Phys. Chem. Earth A/B/C* **32** (15), 1050–1057.
- Kahinda, J. M., Taigbenu, A. E. & Boroto, R. J. 2010 Domestic rainwater harvesting as an adaptation measure to climate change in South Africa. *Phys. Chem. Earth A/B/C* **35** (13), 742–751.
- Khastagir, A. & Jayasuriya, N. 2010 Optimal sizing of rain water tanks for domestic water conservation. *J. Hydrol.* **381** (3), 181–188.
- Liaw, C. H. & Tsai, Y. L. 2004 Optimum storage volume of rooftop rain water harvesting systems for domestic use. *J. Am. Water Resour. Assoc.* **40** (4), 901–912.
- Liuzzo, L., Notaro, V. & Freni, G. 2016 A reliability analysis of a rainfall harvesting system in southern Italy. *Water* **8** (1), 18.
- Lizárraga-Mendiola, L., Vázquez-Rodríguez, G., Blanco-Piñón, A., Rangel-Martínez, Y. & González-Sandoval, M. 2015 Estimating the rainwater potential per household in an urban area: case study in central Mexico. *Water* **7** (9), 4622–4637.
- Marchione, V. 2009 Effetti della riduzione dei volumi irrigui su specie microterme da tappeto erboso in un ambiente della Puglia. *Ital. J. Agron./Riv. Agron.* **4** (Suppl), 961–966.
- Matos, C., Bentes, I., Santos, C., Imteaz, M. & Pereira, S. 2015 Economic analysis of a rainwater harvesting system in a commercial building. *Water Resour. Manage.* **29**, 3971–3986.
- Notaro, V., Liuzzo, L. & Freni, G. 2016 Reliability analysis of rainwater harvesting systems in southern Italy. *Proc. Eng.* **162**, 373–380.
- Pachpute, J. S., Tumbo, S. D., Sally, H. & Mul, M. L. 2009 Sustainability of rainwater harvesting systems in rural catchment of Sub-Saharan Africa. *Water Resour. Manage.* **23** (13), 2815–2839.
- Schiller, E. J. & Latham, B. G. 1987 A comparison of commonly used hydrologic design methods for rainwater collectors. *Int. J. Water Resour. Dev.* **3** (3), 165–170.
- Schmitter, P., Goedbloed, A., Galelli, S. & Babovic, V. 2016 Effect of catchment-scale green roof deployment on stormwater generation and reuse in a tropical city. *J. Water Resour. Plan. Manage.* **142** (7), 05016002.
- Thorntwaite, C. W. 1948 An approach toward a rational classification of climate. *Geog. Rev.* **38**, 55–94.
- Wang, C. H. & Blackmore, J. M. 2012 Supply–demand risk and resilience assessment for household rainwater harvesting in Melbourne, Australia. *Water Resour. Manage.* **26** (15), 4381–4396.
- Ward, S., Memon, F. A. & Butler, D. 2010 Rainwater harvesting: model-based design evaluation. *Water Sci. Technol.* **61** (1), 85–96.
- Willuweit, L. & O’Sullivan, J. J. 2013 A decision support tool for sustainable planning of urban water systems: presenting the dynamic urban water simulation model. *Water Res.* **47**, 7206–7220.
- Wisner, P. & P’ng, J. C. 1983 *OTTHYMO, A Model for Master Drainage Plans, IMPSWM Urban Drainage Modelling Procedures*, 2nd edn. Department of Civil Engineering, University of Ottawa, Ottawa, Ontario, Canada.
- Worm, J. & van Hattum, T. 2006 *Rainwater Harvesting for Domestic Use*. Agromisa Foundation and CTA, Digrafi, Wageningen.
- Yuen, E., Anda, M., Mathew, K. & Ho, G. 2001 Water harvesting techniques for small communities in arid areas. *Water Sci. Technol.* **44** (6), 189–195.
- Zhang, Y., Grant, A., Sharma, A., Chen, D. & Chen, L. 2010 Alternative water resources for rural residential development in Western Australia. *Water Resour. Manage.* **24** (1), 25–36.

First received 22 December 2016; accepted in revised form 4 August 2017. Available online 11 October 2017