The Role of the Temporal Patterns of Rainfall on the Design and Performance of Rainwater Harvesting Systems: the Italian Case

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The Role of the Temporal Patterns of Rainfall on the Design and Performance of Rainwater Harvesting Systems: the Italian Case

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Abstract
Rainwater harvesting (RWH) for indoor use could be a useful practice for a sustainable management of urban water. The impact of the temporal patterns of rainfall on the size of the tank of an RWH system has been analysed in the present work. This analysis was carried out through numerical simulations and was focused on the national Italian territory. Daily rainfall data from 3436 rainfall gauge stations located throughout the Italian territory were considered, and buildings with different catchment areas and numbers of users were considered. The coefficient of variation of the daily rainfall data was used to quantify the temporal variability of the rainfall. Furthermore, analytical expressions have been developed in this work to compute the performance of a rainwater harvesting system (water savings, retention efficiency and overflows) as a function of certain characteristics of the building and of the rainfall regime. The results of the numerical simulations point out the important role of the temporal patterns of rainfall in the design steps of such a system and successfully support the analytical expressions proposed for the performance indicators.

Keywords Rainwater harvesting · Tank size · Rainfall temporal variability · Coefficient of variation · Performance · Analytical expression

1 Introduction

Rainwater harvesting (RWH) has been an essential practice since ancient times, especially in arid, semi-arid and Mediterranean areas where rainfall is scarce and not uniform throughout the year (Campisano et al. 2017; Notaro et al. 2016). In the past, it was mainly utilised for indoor and irrigation purposes to face water shortages. RWH is currently used in more

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applications than in the past and it should therefore be included in water resource management plans and as a tool to mitigate groundwater depletion, reduce tourism-driven water stress in coastal regions, minimise urban floods, recharge aquifers and improve the resilience of water supplies in regions affected by droughts and/or characterised by an intermittent supply of water, such as in the south of Italy (Ali et al. 2025; Wartalska et al. 2024; Torres-Bagur et al. 2019; Nachson et al. 2022; Belmeziti 2024; Piazza et al. 2025). RWH is in fact considered when installing domestic tanks, realising infiltration basins, building rooftop systems, drilling leaking wells and creating permeable pavements.

In this work, we have focused our analysis on the setting up of RWH systems for domestic use considering the tank size as the core of the design. This type of design is usually based on the optimisation of the saving of potable water, while the other performances of the RWH system, with respect to the rainstorm retention efficiency and/or rainwater waste, are subordinate to the desired level of water saving.

In the literature, a great deal of attention has been paid to developing appropriate methodologies to evaluate the performance of RWH systems, to considering the uncertainties that arise due to the considered input data, to including economic aspects and to developing simplified methods. Most of the so far conducted analyses have considered case studies, buildings, villages or towns. However, economic incentives from municipalities and more proposals from designers would be needed to incentivise the diffusion of RWH systems, although some gaps still exist in this direction. Thus, it could be important to: (i) quantify the approximations resulting from simplified design methods; (ii) understand what quantities affect these simplifications; (iii) provide simple formulas to calculate the performance of RWH systems, which would be useful for public administration to provide appropriate incentives and action plans; and (iv) as regards the Italian territory, offer a national-scale analysis of the performance of RWH systems.

Currently, simplified tank sizing methods are based on the mean annual values of the per capita water demand and rainfall depth, as well as on the relevant characteristics of the buildings, that is, the number of inhabitants and the roof area (e.g. UNI 2012), but these methods do not consider the temporal variability of rainfall. Nevertheless, several studies have pointed out the importance of the temporal variability of rainfall on the performance of RWH systems. Jenkins (2007), for instance, investigated the impact of seasonality, while Imteaz et al. (2015) examined the difference in the performance of rainwater harvesting considering dry, wet and average years (5 years for each type). Shiguang and Yu (2021) examined water savings and conducted an economic viability assessment of four Chinese regions with different rainfall regimes by means of time series from 2010 to 2019. Di Chiano et al. (2025) proposed a sizing method for RWH tanks that made use of a probabilistic estimation of the inter-event time. Imteaz et al. (2023) considered the concept of rainfall seasonality to conduct future projections of RWH systems. Pinto et al. (2023) addressed the effects of temporal and spatial variability, through multivariate analysis, considering 46 municipalities in Brazil and 5 year-long rainfall time series. Campisano and Modica (2012) focused on the temporal rainfall patterns of Sicily (Italy) and provided regional regressive equations for the water saving value and overflow discharges. In Campisano et al. (2013), the authors carried out an analysis of the water saving behaviour of 44 sites in Italy and proposed regression curves for different climatic zones, according to the Köppen-Geiger classifications, while Palla et al. (2012) conducted an analysis of RWH performances under various climate zones at a European scale.

Two of the above mentioned issues have been investigated in this work through numerical simulations, using daily rain data obtained from a national rainfall depth database. First, we developed simple analytical expressions to compute performance indicators of an RWH system as a function of some simple characteristics of the building and the rainfall regime, which could be useful for municipalities and practitioners.

The second aspect of this work concerns a comparison, which we conducted for the Italian territory, between the outcomes of the simplified model (UNI 2012) and those of a behavioural method (Palla et al. 2011) to identify any factors that could be responsible for discrepancies. We focused on the role played by the temporal variability of rainfall. The temporal variations of rain are described in this work by means of the rainfall variation coefficient, according to the work of Pinto et al. (2023).

The work is organised as follows: Section 2 describes the used data, the methodologies adopted to implement the behavioural method and the simplified one, and the development of analytical expressions as RWH efficiency indicators. Section 3 presents and compares the results obtained from the numerical simulations with those of the analytical expressions.

2 Materials and Methods

2.1 The RWH System

In the considered RWH system, rainfall is collected from roof surfaces and conveyed, through gutters, to a storage tank. The first and most polluted part of the rainwater, *first flush -ff-*, cannot be utilised for indoor purposes and a first flush diversion has therefore been considered (e.g. Kus et al. 2010; Lay et al. 2024). The rainwater stored in such a tank can be used for toilet flushing, washing machines, floor cleaning, watering plants, etc.

The most important characteristics of buildings in an RWH process for indoor use are the harvesting area, H (usually the roof area), and the number of people, p, who live inside the building: the $H_{pc} = H/p$ ratio is called the *roof area per capita* (Lúcio et al. 2020; Carollo et al. 2022), a parameter that affects the performances of an RWH system to a great extent.

In this work, a group of 5 buildings, with different H_{pc} values, was chosen, considering the most frequent house typologies throughout the Italian territory. These five buildings were hypothesised to be located in areas where rainfall data were available, and simulations of the dynamics of the water level in the tank of the RWH system were performed for each building, thereby generating a large variety of combinations of climatic conditions and building characteristics.

The characteristics of the considered buildings are synthetised in Table 1.

2.2 The Behavioural Model

A water balance of the buildings was computed, at a daily scale, through the Yield After Spillage method (YAS), to simulate the dynamics of the water level inside the tank of the RWH system (Fewkes and Butler 2000; Mitchell 2007; Palla et al. 2011): the continuity equation that was applied to the tank can be written as:

$$V_t = Q_t + V_{t-1} - Y_t - O_t \tag{1}$$

Table 1 Characteristics of the buildings considered in the numerical simulations

Building type	Roof area (m^2)	Number of people	Roof area per capita H_{pc} (m^2/person)
High-rise building HRB	250	100	2.5
Medium-rise building MRB	165	30	5.5
Low-rise building LRB	100	10	10
Detached house DH	100	4	25
Villa V	400	4	100

where V_t and V_{t-1} are the volumes of rainwater contained in the tank after both the inflow and yield in day *t* and day *t-1*, respectively; Q_t(the inflow) is the rainwater volume that can enter the tank in day *t*; Y_t is the rainwater volume supplied to the users in day *t*, and O_t is the volume that overflows from the tank to the sewerage system in day *t*. The inflow to the tank is computed as:

$$Q_t = (\phi \cdot R_t - ff_t) \cdot H \tag{2}$$

where ϕ is the runoff coefficient, R_t is the rainfall depth, H is the harvesting area of the building, and ff_t is the depth of the first flush rain. Values of 0.8 and 1 mm (for a rainy day) were used for the runoff coefficient and the first flush considered in this work, respectively (Farreny et al. 2011; Amin et al. 2013).

The terms Y_t and V_t in Eq. (1) are computed in the YAS method as follows:

$$Y_t = min\left\{ \begin{array}{c} D_t \\ V_{t-1} \end{array} \right. \quad and \quad V_t = min\left\{ \begin{array}{c} V_{t-1} + Q_t - Y_t \\ S - Y_t \end{array} \right. \tag{3}$$

where D_t is the water demand in day *t* and S is the storage capacity of the tank. The water demand depends on the number of inhabitants in the building, and it is estimated as the product of $D_t = p \cdot d$, where *p* is the number of people who live in the building and *d* is the per-capita water demand for non-potable use, which was assumed constant and equal to $50\ l/(d \cdot p)$, as suggested in the Italian National Standards (UNI 2012). The tank was considered empty at the beginning of the simulations (Mitchell 2007).

In order to size an RWH system using a behavioural model, it is suggested that the time series should be several years long and possibly continuous: Palla et al. (2011), for instance, suggested using a 30 year-long series, Agudelo-Vera et al. (2013) used a 25 year-long series, while Mitchell (2007) and Geraldi and Ghisi (2017) considered a 10 year-long series as being acceptable.

2.3 The Simplified Method

National standards or guidelines often suggest simplified methods for the sizing of RWH systems (e.g. the Italian (UNI 2012), British (BS 2013) and French (RF 2009) standards). These methods are based on dimensionless parameters (Schiller and Latham 1992; Fewkes and Butler 2000; Palla et al. 2011): the demand fraction *D/Q* (i.e., the ratio between the mean annual values of the non-potable demand and the mean annual inflow) and the storage fraction *S/Q* (i.e., the tank volume over the mean annual inflow).

The simplified method suggested in the Italian Standard (UNI 2012) has been considered in this work. This standard is suggested for detached or semi-detached family homes when there is a constant rainwater demand over the year. The formula used for sizing the tank capacity can be written as follows:

$$\frac{S}{Q} = \begin{cases} 0.09 & if\,\frac{D}{Q} > 1 \\ 0.09\frac{D}{Q} & if\,\frac{D}{Q} < 1 \end{cases} \tag{4}$$

The coefficient 0.09 in Eq. (4) also includes a safety factor equal to 1.5, which has been suggested to take into account variations in the rainfall regime. The case with $D/Q<1$ refers to a rainwater surplus condition, that is, the mean annual volume of requested non-potable water is smaller than the mean annual volume of rain that can be collected, while the $D/Q>1$ case refers to a rainwater deficit condition. As can be seen from Eq. (4), the simplified method does not account for the temporal variability of rainfall in different locations for the optimisation of the tank size.

2.4 RWH System Efficiency Indicators

In this section, analytical expressions are provided to evaluate RWH performances related to water savings, rainwater retention and rainwater utilisation efficiencies. The proposed indicators allow the efficiency of an RWH system to be computed by referring to simple quantities regarding the building characteristics and the rainfall regime. Efficiency indicators were developed for the case of a constant water demand, and the complete derivation of these expressions can be found in the Appendix (Online Resource), where the degree of accuracy of the proposed formulas is also discussed.

The analytical expressions are different for whenever a rainwater deficit condition ($D/Q>1$) or a rainwater surplus condition ($D/Q<1$) occurs.

2.4.1 Water Saving Efficiency

Water saving efficiency, E_{WS}, is the percentage of the non-potable water demand that is satisfied with rainwater. If a behavioural model is adopted, E_{WS} can be computed as

$$E_{WS} = \frac{\sum_{t=1}^{T} Y_t}{\sum_{t=1}^{T} D_t} \tag{5}$$

where T is the number of time steps used in the simulations, the numerator is the total yield of the rainwater, and the denominator is the total water demand for the same period. E_{ws} varies between 0 and 1, and it grows non-linearly as the tank size, S, grows, with a very mild slope for large E_{ws} values (e.g., Lúcio et al. 2020).

If the main purpose of an RWH system is the reduction of the consumption of potable water, E_{ws} should be as large as possible, but a tank capacity can be too large and/or not economically sustainable for practical situations (Butera et al. 2021). In order to avoid increasing the size of the tank and only obtaining a limited efficiency gain, a "target efficiency" η (0–1) (Gnecco et al. 2013; Carollo et al. 2022) can be introduced in the design phase of the tank capacity: the design water saving efficiency, $E_{ws,\,design}$, is reduced with respect to the maximum value as:

$$E_{ws,\,design} = \eta \cdot E_{ws,\,max} \tag{6}$$

The numerator of Eq. (5) should be maximised to obtain an analytical expression of $E_{ws,\,max}$. The numerator is maximum in the deficit condition when all the available rainwater, Eq. (2), is supplied to the users of the building and overflow is avoided. The numerator is instead maximum in the surplus condition when the demand is satisfied, that is, it is equal to the cumulated demand. However, the initial condition of the rainwater volume in the tank (empty or full) can have a slight effect on the water saving value.

The expression of the maximum water saving efficiency is:

$$E_{ws,max} = \begin{cases} \frac{Q}{D} = \frac{H(\phi\, h - ff^*)}{d \cdot p \cdot 365} & if \frac{D}{Q} > 1 \\ 1 & if \frac{D}{Q} < 1 \end{cases} \tag{7}$$

where h is the mean annual rainfall depth and ff^* is the mean annual first flush (the mean cumulated first flush in one year, which is always lower than the mean annual net rainfall ϕh), d is the per capita daily water consumption, p is the number of people who live in the building and 365 is the number of days in one year. Therefore, when using Eq. (6) we obtain:

$$E_{ws,design} = \begin{cases} \eta \cdot \frac{\phi}{365 \cdot d} \cdot H_{pc} \cdot h - \eta \cdot \frac{ff^*}{365 \cdot d} \cdot H_{pc} & if \frac{D}{Q} > 1 \\ \eta & if \frac{D}{Q} < 1 \end{cases} \tag{8}$$

As can be seen, $E_{ws,\,max}$ and $E_{ws,\,design}$ are obtained, in rainwater deficit conditions, as the sum of two terms: the first one depends on the mean annual rainfall depth, while the second one is affected by the temporal variability of rainfall through ff^*. The water saving efficiency linearly depends on H_{pc} for a certain location with a given mean annual rainfall depth and cumulated first flush.

2.4.2 Retention Efficiency

The retention efficiency measures the capacity of an RWH system to retain rainwater that would otherwise enter the sewerage system. We computed the retention efficiency of a tank sized according to a certain water saving design: $E_{r,\,ws\,design}$. The retention efficiency is defined as the ratio between the volume of stored water and the volume of inflow water over the whole analysed period, which can be written as:

$$E_{r,wsdesign} = \frac{\sum_{t=1}^{T}(Q_t - O_t)}{\sum_{t=1}^{T} Q_t} \cong \frac{E_{ws,design} \cdot D}{Q} \tag{9}$$

Substituting Eq. (8) in Eq. (9), we obtain:

$$E_{r,wsdesign} = \begin{cases} \eta & if \frac{D}{Q} > 1 \\ \eta \frac{1}{H_{pc}} \cdot \frac{365 \cdot d}{\phi h - ff^*} & if \frac{D}{Q} < 1 \end{cases} \tag{10}$$

Equation (10) shows that, for a fixed roof area per capita, the retention assumes a constant value of η for low values of h, which correspond to a rainwater deficit condition, while $E_{r,\ wsdesign}$ starts to decrease as h increases, like part of a hyperbola, in the rainwater surplus condition. The roof area per capita H_{pc} contributes by moving part of the hyperbola down as H_{pc} increases.

The impact of the temporal variability of rainfall in Eq. (10) is present in ff^*, which is usually small compared to ϕh. It emerges, from Eq. (9), that the same retention efficiency is reached for the same building when placed in locations with the same mean annual rainfall depth, but different rainfall patterns, if the tank is dimensioned to achieve the same $E_{ws,\ design}$.

2.4.3 Overflow Ratio

The overflow ratio indicator, *OVR*, is here proposed to quantify the collected rainwater waste. *OVR* is the ratio between the rainwater overflow volume and the rainwater demand in the same period, and it shows how much rainwater is wasted, compared to the demand. The overflow ratio of an RWH system, sized according to a certain $E_{ws,\ design}$ value, can, with some approximation, be written as:

$$OVR_{wsdesign} = \frac{\sum_{t=1}^{T} O_t}{\sum_{t=1}^{T} D_t} \cong \frac{Q}{D} - E_{ws,design} \tag{11}$$

Substituting Eq. (8) in Eq. (11), we obtain:

$$OVR_{wsdesign} = \begin{cases} \frac{Q}{D}(1-\eta) = (1-\eta) \cdot H_{pc} \cdot \left(\frac{\phi \cdot h - ff^*}{365 \cdot d}\right) & if \frac{D}{Q} > 1 \\ \frac{Q}{D} - \eta = \frac{\phi}{365 \cdot d} \cdot H_{pc} \cdot h - \left(\frac{ff^*}{365 \cdot d} \cdot H_{pc} + \eta\right) & if \frac{D}{Q} < 1 \end{cases} \tag{12}$$

Equation (12) shows that the overflow ratio is a linear function of h, and it is characterised by a slope that increases from a rainwater deficit condition to a rainwater surplus condition. The roof area per capita, H_{pc}, contributes by changing both the slope and the intercept of the linear functions. Moreover, $OVR_{wsdesign}$ depends linearly on the mean annual rainfall depth for a certain H_{pc} value, while the cumulated first flush defines the value of the intercept of the line with the ordinate axis on the h-$OVR_{wsdesign}$ plane.

2.5 Rainfall Data

The RWH simulations conducted with the behavioural model need daily-scale rainfall datasets as input. The Italian climate database provided by SCIA-ISPRA (ISPRA 2023) contains data from meteorological stations located throughout the Italian territory. However, the length of the rainfall depth series available at a daily scale, their start dates and their end dates are all different, and they can contain interruptions (missing data). The length of the series and missing data can in fact affect the numerical simulations of the water levels inside the tank. Therefore, only series that respect the following two requirements were selected for the RWH simulations: (i) the series had to be at least 15 years long; (ii) each calendar day had to be present in at least 80% of the years. A total of 3436 stations, distributed, with a variable density, over the whole Italian territory, complied with these constraints. The time extension varied between 15 and 73 years. The percentage of missing data in a series was lower than 5% in more than 73% of the stations and was lower than 10% in 94% of the stations. Just in 1% of the total number of stations was the percentage of missing data between 15% and 20%.

The locations and the lengths of the considered series are shown in Fig. 1a. The distribution of the mean annual rainfall depth over the Italian territory is shown in Fig. 1b, while the rainfall Coefficient of Variation obtained from the daily rainfall data used in this work is shown in Fig. 1c. The mean annual rainfall depth shows a well-known pattern (Desiato et al. 2015), with greater rainfall depths in the North, in particular in the Alps, and smaller rainfall depths in the South of Italy. As far as the Coefficient of Variation is concerned (Fig. 1c), the highest values of CV can mainly be observed along the south-eastern coasts of the peninsula and for the main islands. It is interesting to observe that the geographical distribution of the highest values of CV closely resembles the geographical distribution of the ratio between the 24-h maximum value and the local mean annual rainfall depth that was shown, for larger values than 0.35, in Mazzoglio et al. (2020).

As can be seen from Fig. 1d, most of Italy has CV values in the 2-3.5 range. The rainfall depth is more uniform (low CV) in the North-East and in part of the Centre and Central-Southern part of Italy.

3 Results and Discussion

The results obtained from the application of the behavioural method are shown in Fig. 2 for a target efficiency, η, equal to 0.8; therefore, the tank capacity allows 80% of the possible maximum water savings to be obtained. A second scenario, for $\eta = 0.6$, was considered, but the results have not been reported for the sake of brevity. The latter scenario produced lower tank volumes and lower designed water saving efficiencies, in agreement with Eq. (8). Only the results of the simulations that provided a greater S/Q value than 0.01 have been retained, as it is a requisite to consider that the daily temporal resolution is accurate (Fewkes and Butler 2000). The designed water saving efficiency and the tank volumes necessary to obtain such a value are shown in Fig. 2 for three typologies of buildings that are common throughout the Italian territory. The numerosity of points is lower for individual villas, as shown in Fig. 2, because the $S/Q > 0.01$ requirement is rarely satisfied in rainy locations.

According to Eq. (8), the designed water saving efficiency increases as the roof area per capita increases. Furthermore, $E_{ws,\ design}$ shows a similar pattern to the mean annual rainfall depth pattern (Fig. 1b) for both medium-rise buildings (MRB) and for detached houses (DH). This outcome can be expected from Eq. (8), considering that the demand fraction is usually $D/Q > 1$ in the MRB and DH cases. Finally, increasing the roof area per capita (see the Villa case), the whole territory shows a higher designed water saving than 0.75, because it reaches the target efficiency value $\eta = 0.8$, in agreement with Eq. (8), with the exception of 448 locations (13%), where it is just slightly smaller than 0.8 (0.77–0.8 range), because the tank is assumed empty at the beginning of the simulations.

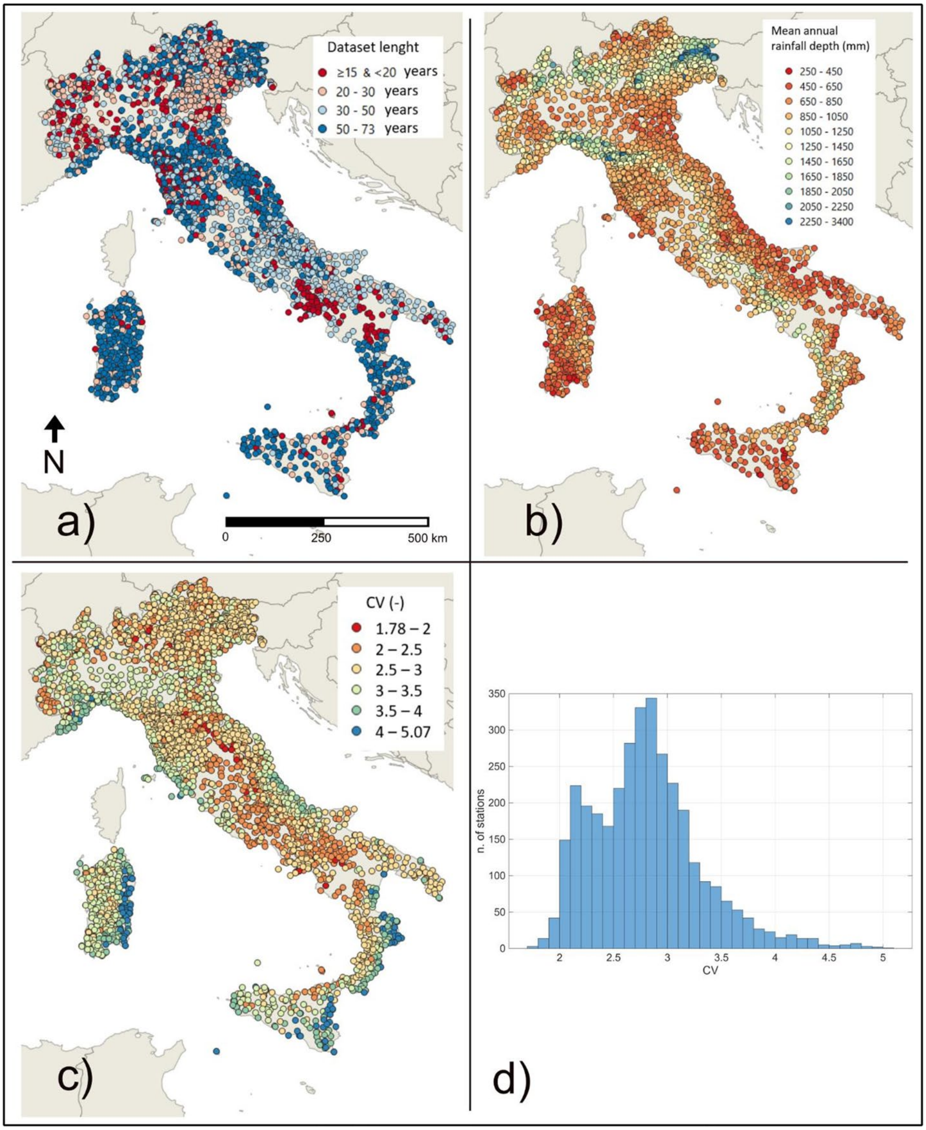

Fig. 1 Locations of the 3436 considered rain gauges and characteristics of their rainfall datasets: **a** map of the lengths of the daily rainfall series (years); **b** map of the mean annual rainfall depths (mm); **c** map of the Coefficient of Variation of the rainfall series (non-dimensional); **d** statistical distribution of the Coefficient of Variation

It can be seen, from the central and lower rows in Fig. 2, that the most widespread tank capacity is in the 2–5 m^3 range (orange), regardless of the typology of the buildings, although there are different geographical and statistical distributions. The role H_{pc} plays in determining the tank size is complex. In some cases, the tank size always increases when H_{pc} increases (e.g. point A in Fig. 2 - Cozzo Spadaro, in Sicily), while in others the tank size decreases moving from the MRB case to the DH case, and it then increases from the

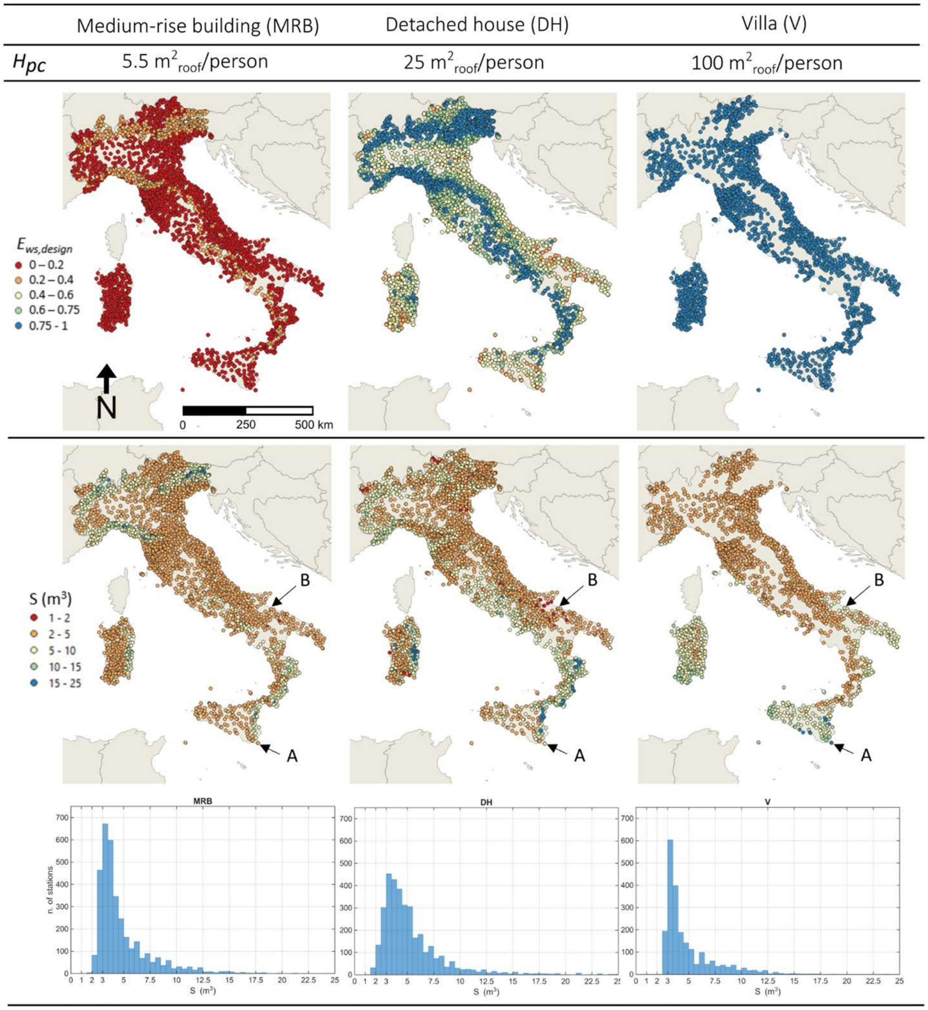

Fig. 2 Target efficiency (η) 0.8. Maps of the water saving efficiency (non-dimensional - upper row) and tank size (m^3 - central row) for three types of buildings. Lower row: absolute frequency of the tank size

DH case to the V case (e.g. point B in Fig. 2 -Masseria San Francesco, in Apulia). This non-intuitive behaviour becomes clear in Fig. 3, where the results of the numerical simulations of all the five building typologies listed in Table 1 at each rainfall data location are shown as a function of the demand fraction, the storage fraction and the coefficient of variation of the rainfall (CV). The tank variations for locations A and B were in fact obtained by moving from low H_{pc} values to high ones, that is, for decreasing *D/Q*. The points that refer to locations A and B for the different buildings are shown in Fig. 3, where *D/Q* decreases for a certain location (i.e. fixed CV), moving from the MRB house to the Villa and, depending on the *D/Q* values, *S/Q* first increases and then decreases. Fewkes (1999) reported a similar type of behaviour for the surplus case in Nottingham (UK).

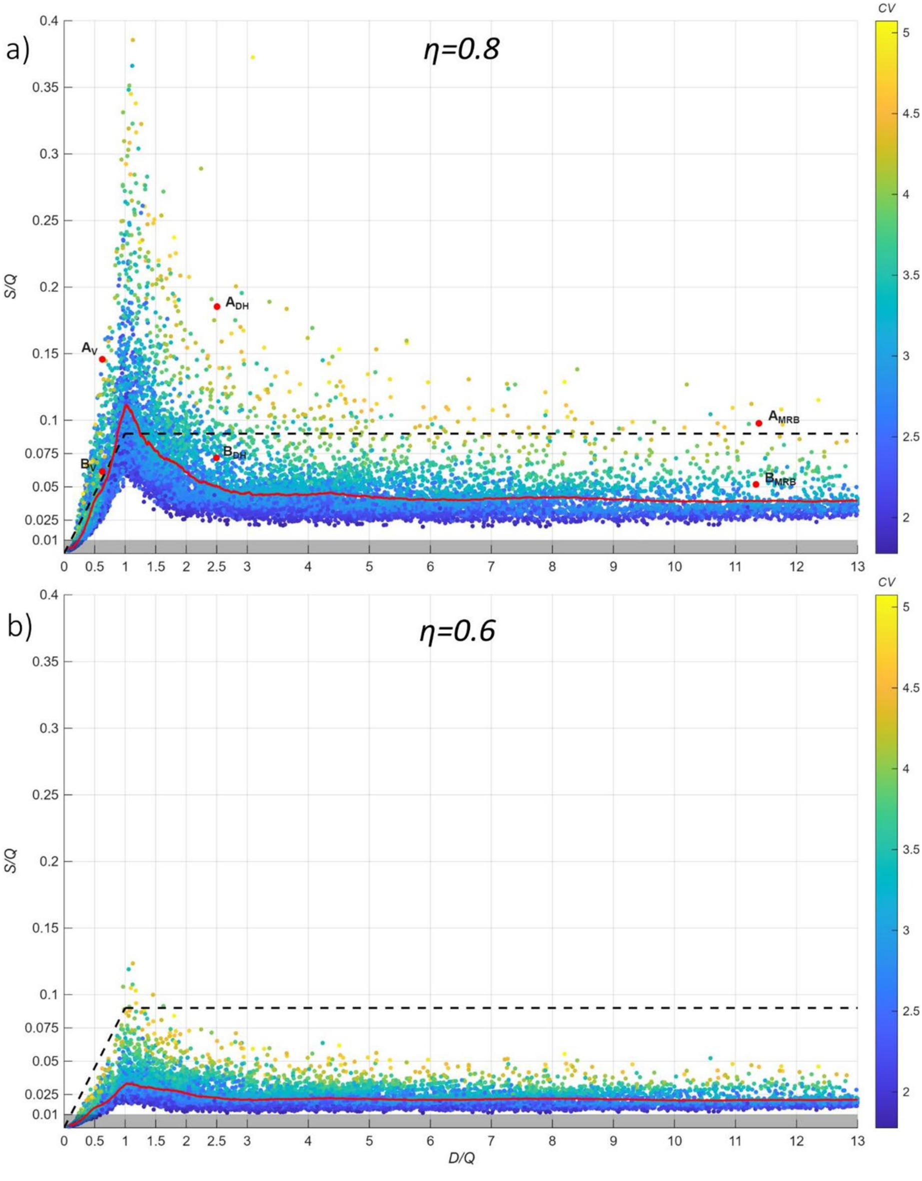

Fig. 3 The dots represent the values of storage fraction *S/Q*, as a function of the demand fraction *D/Q* and of the coefficient of variation *CV*. The mean value of *S/Q* is shown with the red line. The dashed line represents the simplified sizing method of the Italian Standards, while the grey belt hides the results that do not comply with the $S/Q \geq 0.01$ constraint. Graph (**a**): the $\eta = 0.8$ case; points A and B represent the results of the two locations considered in Fig. 2. Graph (**b**): the $\eta = 0.6$ case. *S/Q* can be obtained, and in turn the storage capacity *S* for a location, since *D/Q* and the *CV* are available

The arrangement of the coloured dots in Fig. 3 clearly shows that the temporal distribution of the rainfall, which is represented by the coefficient of variation, has an impact on the relationship between the storage fraction and the demand fraction. It can be noted that *S/Q* increases for a fixed *D/Q* value as the coefficient of variation increases.

In order to clarify this aspect, a medium-rise building (Table 1) was considered in three different locations with similar annual rainfall depths but different CVs, and the sizes of the tank were computed for the same target efficiency ($\eta = 0.8$). The results are shown in Table 2, where it can be seen that the tank capacity varies between 2.7 m^3 and 6.8 m^3.

In Fig. 3, the simplified method is compared with the mean *S/Q* values obtained from the simulations (red line). It can be seen that the two types of behaviour are tuned when $D/Q < 1$ but are not for $D/Q > 1$. Indeed, both methods indicate that the storage capacity *S* has to increase in the surplus conditions whenever *D* increases in order to store the available rainwater volumes, while, in the deficit conditions, only the simulations demonstrate that it is not useful to maintain a large storage capacity when the demand increases.

Unlike the numerical simulations, the simplified Italian method is not affected by the target efficiency or by the rainfall coefficient of variation. Figure 3a, which considers a target efficiency of 0.8, shows that the deviations between the simplified method and the analytical method are significant for both signs, that is, positive and negative. When a lower target efficiency is considered to size a tank, for instance $\eta = 0.6$ (Fig. 3b), the tank capacities are reduced, and the simplified model overestimates the tank volume.

The numerical simulations were also used to test the efficiency indicators of the RWH system, that is, Eqs. (8), (10) and (12) proposed in this work. The comparison is shown in Fig. 4: the behaviour of each indicator is represented as a function of the annual mean rainfall depth at each location for two target efficiencies: $\eta = 0.6$ and $\eta = 0.8$. The different colours of the dots refer to the five analysed building typologies, and each colour reflects a different value of the roof area per capita parameter. Overall, 3436 dots (the number of the considered rain gauge stations) are present for each colour (with the exception of Villas, which show a lower number of results due to the $S/Q > 0.01$ requirement). The solid black lines represent Eq. (8) for the water saving efficiency, Eq. (10) for the retention efficiency, and Eq. (12) for the overflow ratio.

An analysis, the results of which have not been reported for the sake of brevity, showed that ff^* varies between 50 mm and 180 mm and decreases as CV increases. The mean value, that is, $ff^* = 107$ mm, was used for the analytical formulas shown in Fig. 4. A comparison with the numerical results shown in Fig. 4 demonstrates the validity of this assumption.

The diagrams in Fig. 4 show that the numerical results fit the proposed theoretical models very well for both of the considered target efficiency values. The numerical data exhibit behaviour that is essentially driven by the annual mean rainfall depth for all the indicators. The numerical data show a spread around the solid line, which, as can be observed, is limited. The temporal variability of the rainfall instead plays a role in the step concerning the size of the tank.

Table 2 Effects of the Temporal pattern of rainfall on the designed tank capacity

Location	h (mm)	CV	S (m^3)	D/Q	S/Q
Ascoli Satriano – South	641	2.42	2.7	8.18	0.04
Casale Monferrato – North	623	3.41	3.4	8.48	0.053
Muravera – the Island of Sardinia	637	4.83	6.8	8.24	0.102

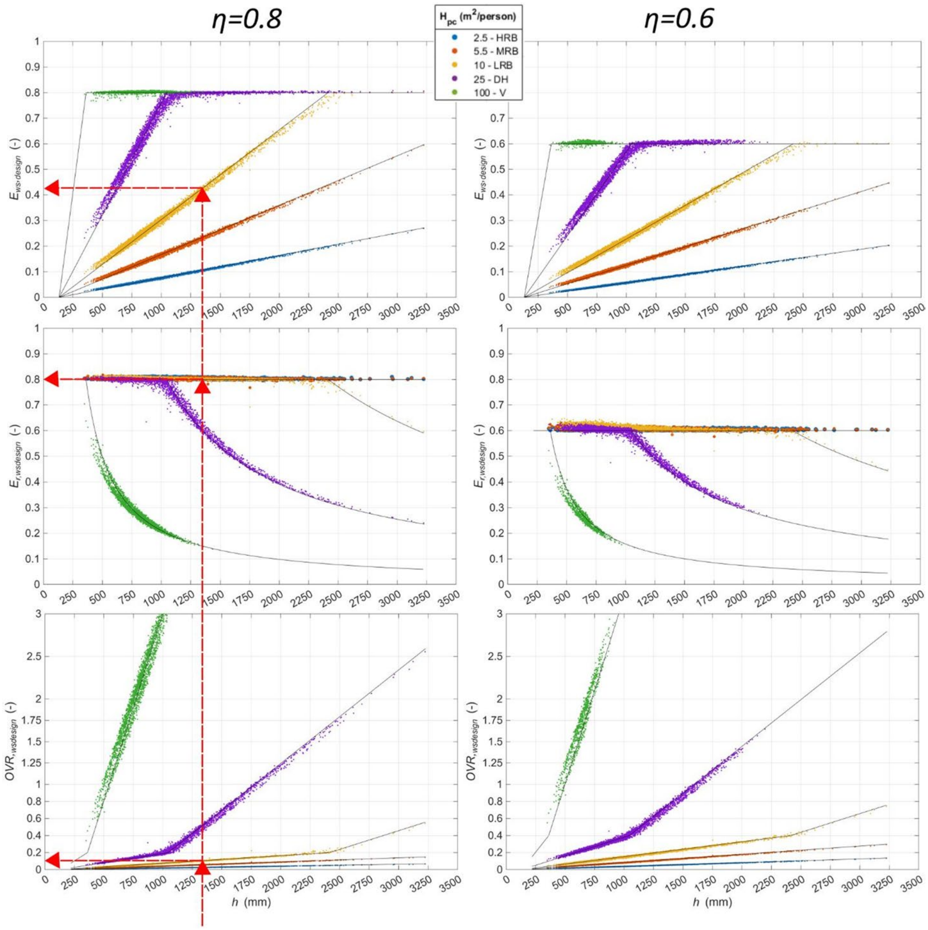

Fig. 4 The diagrams show, from the top to the bottom, the numerical results and analytical solutions as a function of the mean annual rainfall depth h for: the optimal water saving efficiency, $E_{ws,\ design}$ (solid line for Eq. 8), the retention efficiency, $E_{r,\ wsdesign}$ (solid line for Eq. 10), and the overflow ratio, $OVR_{wsdesign}$ (solid line for Eq. 12). The different lines refer to the different considered H_{pc} values. η is the target efficiency used to size the RWH tank. The values of the efficiency indicators are obtained as shown by the red arrows for h = 1300 mm and H_{pc}=10 m^2/person

By comparing the case pertaining to a target efficiency of 0.8 with the case in which the target efficiency is equal to 0.6, it can be observed that, as expected, both the water saving efficiency and the retention efficiency decrease as the target efficiency decreases, while the overflow ratio increases.

Each image in Fig. 4 can be used to identify $E_{ws,\ design}$, $E_{r,wsdesign}$ and $OVR_{wsdesign}$ for a certain η and a given building (H_{pc} value), as well as the mean annual rainfall depth on the y axis (red arrows in Fig. 4).

A flow chart is given in Fig. 5 to show the use of our results.

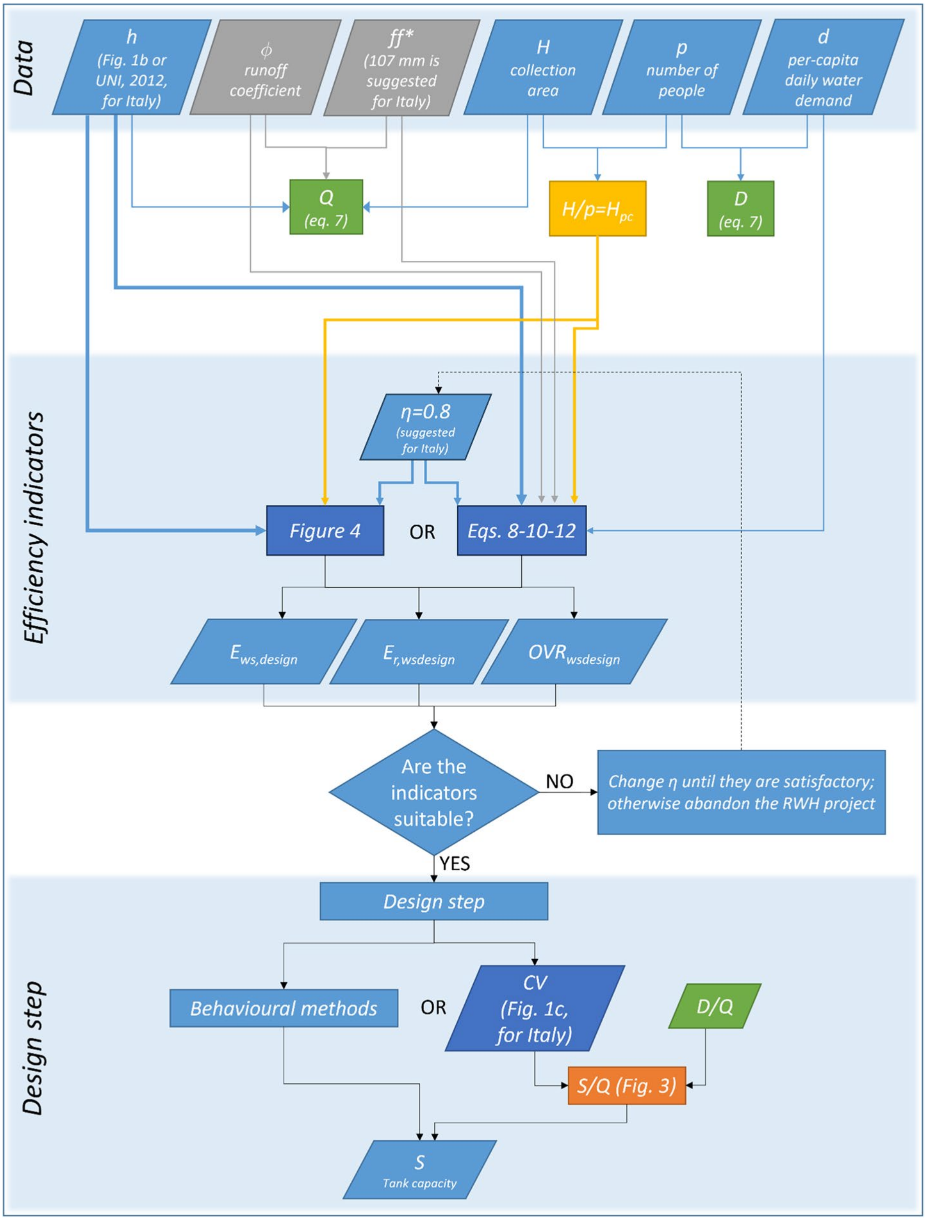

Fig. 5 Flow chart of the overall method, which shows the process proposed to compute the efficiency indicators of an RWH system and to design the tank capacity

4 Conclusions

The impact of the temporal variability of the rainfall depth on the sizing of the capacity of an RWH tank has been investigated in this work at a national scale. The analysis considered the Italian territory and daily rainfall data from 3436 rain gauge stations. The results of the numerical simulations have shown that the rainfall coefficient of variation is responsible for differences in the storage fractions for a fixed demand fraction, which could reach one order of magnitude, and that simplified methods can lead to overestimating or underestimating the capacity of an RWH tank. Furthermore, the simplified methods do not capture the decrement of the storage fraction when the demand fraction is larger than unity.

Another aim of this work has been to develop analytical expressions to compute performance indicators of RWH systems. These expressions were successfully validated through the numerical simulations, and they offer new tools that can be used by municipalities and practitioners to assess the performance of RWH systems in a simple way as the average annual rainfall depth, the average non-potable water demand, the runoff coefficient and cumulated first flush and the collection area are all used as input. Municipalities could easily adopt the method proposed in this work considering the flow chart of Fig. 5.

The contribution of the present manuscript does not exhaust the addressed topics. The analysis of climate change effects and the presence of uncertainties, accompanied by economic assessments, may be interesting developments for research, and an effort could be made to include the temporal variability of rainfall in simplified methods to help and improve the sizing of RWH systems.

Appendix

For the purposes of the formulas developed hereafter, the mean annual inflow and demand values (Q and D, respectively) are related to the cumulated values of inflow and demand over the entire analysed period, which are called Q_c and D_c, respectively, and the demand fraction can therefore be expressed through the mean annual values or the cumulated values:

$$Q = \frac{\sum_{t=1}^{T} Q_t}{n_{years}} = \frac{Q_c}{n_{years}} \tag{A0.1}$$

$$D = \frac{\sum_{t=1}^{T} D_t}{n_{years}} = \frac{D_c}{n_{years}} \tag{A0.2}$$

where n_{years} is the number of considered years, and T is the amount of data. When a daily temporal resolution is chosen, as in the present work, T is the number of days of the analyzed period.

Water saving efficiency

In order to obtain the expression of $E_{ws,max}$, we considered that the water saving efficiency is maximum when the numerator of Eq. (5) is maximized, because the denominator does not change. However, the two conditions, deficit (D/Q>1) and surplus (D/Q<1), should be discussed separately.

The numerator in the deficit condition is maximum when all the available rainwater, that is, Eq. (2), is supplied (through an appropriate tank) to the building users, so that the overflow is always zero. It is possible to derive, from Eq. (1), the expression of the volume of water supplied when the overflow is null:

$$Y_t = Q_t - (V_t - V_{t-1}) \tag{A1}$$

which, for the whole analysis period, leads to:

$$\sum_{t=1}^{T} Y_t = \sum_{t=1}^{T} Q_t - \sum_{t=1}^{T} (V_t - V_{t-1}) \tag{A2}$$

Eq. (A2) shows that, when considering T time steps, the total yield is affected by the initial and final rainwater volumes in the tank, where

$$\sum_{t=1}^{T} (V_t - V_{t-1}) = V_T - V_0 = \Delta \tag{A2bis}$$

In the present work, V_0 is zero and therefore $\Delta = V_T$. Thus, the total volume supplied, Eq. (A2), is equal to the total inflow, but only if the tank is empty at the end of the last day of the simulation (T day).

In the surplus condition, the goal is to satisfy the entire water demand, and the total overflow over the whole analyzed period is thus the difference between the total rainwater inflow and the total demand:

$$\sum_{t=1}^{T} O_t = \sum_{t=1}^{T} Q_t - \sum_{t=1}^{T} D_t \tag{A3}$$

therefore, through Eq. (1), the total yield becomes:

$$\sum_{t=1}^{T} Y_t = \sum_{t=1}^{T} D_t - \Delta \tag{A4}$$

As far as the denominator of Eq. (5) is concerned, given that the per capita water demand, *d,* is considered constant, the cumulated demand can be written explicitly as:

$$D_c = d \cdot p \cdot 365 \cdot n_{years} \tag{A5}$$

and it is possible to write the expression for $E_{ws,max}$ through Eq. (5) as:

$$E_{ws,\max} = \begin{cases} \frac{Q_c}{D_c} - \frac{\Delta}{D_c} & if \frac{D}{Q} > 1 \\ 1 - \frac{\Delta}{D_c} & if \frac{D}{Q} < 1 \end{cases} \tag{A6}$$

Next, all the quantities in Eq. (A6) that refer to the whole period, *T,* are replaced by the more useful annual-based quantities: the mean annual rainfall depth, *h* and the mean annual cumulated first flush, *ff**. In the same way, the Q_c/D_c ratio is replaced by *Q/D* (see Eqs. (A0.1) and (A0.2)).

$$E_{ws,\max} = \begin{cases} \frac{Q}{D} - \frac{\Delta}{D_c} & if \frac{D}{Q} > 1 \\ 1 - \frac{\Delta}{D_c} & if \frac{D}{Q} < 1 \end{cases} \tag{A7}$$

And, through Eq. (6), the designed water saving efficiency can be written as:

$$E_{ws,design} = \begin{cases} \eta \frac{Q}{D} - \eta \frac{\Delta}{D_c} & if \frac{D}{Q} > 1 \\ \eta - \eta \frac{\Delta}{D_c} & if \frac{D}{Q} < 1 \end{cases} \tag{A8}$$

Eq. (A8) can be re-written in the form of Eq. (A9) to obtain simpler expressions.

$$E_{ws,design} = \begin{cases} \eta \frac{Q}{D} \left(1 - \frac{\eta D}{\eta Q} \frac{\Delta}{D_c}\right) = \eta \frac{Q}{D} \left(1 - k_{1,d}\right) & if \frac{D}{Q} > 1 \\ \eta \left(1 - \frac{\Delta}{D_c}\right) = \eta \left(1 - k_{1,s}\right) & if \frac{D}{Q} < 1 \end{cases} \tag{A9}$$

where simple expressions are obtained if the $k_{1,d}$ (deficit condition) and $k_{1,s}$ (surplus condition) terms are much smaller than one:

$$E_{ws,design} = \begin{cases} \eta \frac{Q}{D} & if \frac{D}{Q} > 1 \\ \eta & if \frac{D}{Q} < 1 \end{cases} \tag{A10}$$

The $k_{1,d}$ and $k_{1,s}$ terms depend on $\Delta = V_T - V_0$ and, through Eq. (3), it can be seen that the maximum value of V_T is *S,* the tank capacity. Thus, through Eqs. (A0.1) and (A0.2), it is possible to write:

$$\max\left(k_{1,d}\right) = \frac{S}{Q \cdot n_{years}} \tag{A11}$$

$$\max\left(k_{1,s}\right) = \frac{S}{D \cdot n_{years}} \tag{A12}$$

S/Q and S/D, which are quantities that can assume different values according to the kind of building and the rainfall regime, appear in Eqs. (A11) and (A12), but the suggestions of the Italian simplified method have been considered for the aims of this discussion. The Italian Standards suggest S/Q = 0.09 when a deficit condition occurs, and S/D=0.09 when a surplus condition occurs. $n_{years} > 10$ is usually used, and $n_{years} = 10$ was therefore prudentially chosen to maximize $k_{1,d}$ and $k_{1,s}$, and, under these conditions, both the maximum values of $k_{1,d}$ and $k_{1,s}$ were equal to 0.009, which means a maximum overestimation of 0.9% was expected whenever these values were neglected. Such a difference can certainly be considered negligible, and thus the water saving efficiency was computed with the simplified expression, that is, Eq. (A10).

Retention efficiency

The difference between the inflow and the overflow in a day for a certain tank capacity can be calculated from Eq. (1) as the volume of stored rainwater (sw_t):

$$sw_t = Q_t - O_t = V_t - V_{t-1} + Y_t \tag{A13}$$

Hence, the retention efficiency can be written as:

$$E_{r,wsdesign} = \frac{\sum_{t=1}^{T} sw_t}{\sum_{t=1}^{T} Q_t} = \frac{\sum_{t=1}^{T} Y_t + \sum_{t=1}^{T} (V_t - V_{t-1})}{\sum_{t=1}^{T} Q_t} = \frac{\sum_{t=1}^{T} Y_t + \Delta}{\sum_{t=1}^{T} Q_t} = \frac{\sum_{t=1}^{T} Y_t}{\sum_{t=1}^{T} Q_t}\left(1 + \frac{\Delta}{\sum_{t=1}^{T} Y_t}\right) \tag{A14}$$

where the subscript denotes that the tank has already been defined according to a certain designed water savings efficiency value. Writing the total yield as a function of the designed water saving efficiency and by means of Eqs. (A0.1) and (A0.2), we obtain:

$$E_{r,wsdesign} = \frac{E_{ws,design} \cdot D_c}{Q_c}\left(1 + \frac{\Delta}{\sum_{t=1}^{T} Y_t}\right) = \frac{E_{ws,design} \cdot D}{Q}\left(1 + k_2\right) \tag{A15}$$

It could be useful to neglect k_2 to obtain simpler expressions. The maximum value of k_2 is obtained by writing the expression for k_2 as a function of $E_{ws,design}$, considering Eqs. (A0.1) and (A0.2), and assuming S as the maximum value of Δ:

$$\max\left(k_2\right) = \frac{S}{\sum_{t=1}^{T} Y_t} = \frac{S}{D \cdot n_{years} \cdot E_{ws,design}} \tag{A16}$$

As for the water saving efficiency, S/D = 0.09 and S/Q = 0.09 are assumed and, prudentially, n_{years}=10.

In the surplus condition, the simplified expression $E_{ws,\,design}=\eta$ is used to obtain max(k_2) <0.05, and when it is neglected, the error is smaller than 5%, while η must be larger than 0.18, which is a realistic condition.

In the deficit condition, $E_{ws,design} = \eta \frac{Q}{D}$ and S/Q=0.09, and the maximum k_2 value is the same as for the surplus condition, so that η must be higher than 0.18 to limit the underestimation error to 5% when k_2 is neglected.

Overflow ratio

The expressions of the overflow ratio is obtained for the tank of an RWH system sized according to a specific $E_{ws,design}$ value.

Using Eq. (1), it is possible to write:

$$OVR_{wsdesign} = \frac{\sum_{t=1}^{T} O_t}{\sum_{t=1}^{T} D_t} = \frac{\sum_{t=1}^{T} Q_t - \sum_{t=1}^{T} Y_t - \Delta}{\sum_{t=1}^{T} D_t} = \frac{Q}{D} - E_{ws,design} - \frac{\Delta}{\sum_{t=1}^{T} D_t} \tag{A18}$$

Eq. (A18) can be written as:

$$OVR_{wsdesign} = \left(\frac{Q}{D} - E_{ws,design}\right) \cdot \left(1 - \frac{1}{\frac{Q}{D} - E_{ws,design}} \frac{\Delta}{D \cdot n_{years}}\right) \tag{A19}$$

In the deficit condition, using Eq. (A10) we obtain:

$$OVR_{wsdesign} = \frac{Q}{D}(1-\eta) \cdot \left(1 - \frac{\Delta}{Q(1-\eta) \cdot n_{years}}\right) = \frac{Q}{D}(1-\eta) \cdot (1 - k_{3,d}) \tag{A20}$$

and the aim is to neglect $k_{3,d}$ to obtain a simpler expression. The maximum value of $k_{3,d}$ is obtained for $\Delta = S$, and by considering S/Q = 0.09 and prudentially $n_{years} = 10$, we obtain:

$$\max(k_{3,d}) = \frac{S}{Q(1-\eta) \cdot n_{years}} = \frac{0.009}{(1-\eta)} \tag{A21}$$

From Eq. (A21), it emerges that $k_{3,d}$ has an impact on the OVR_{design} values of less than 5% for $\eta < 0.82$ and of less than 9% for $\eta < 0.9$. For η values close to 1, according to Eq. (A21) $k_{3,d}$ tends to infinity and in order to overcome this discrepancy, the complete expression of $E_{ws,\ design}$, that is, Eq. (A8), is inserted into Eq. (A18) so that, as expected, the overflow is null, because all the rainwater is used

$$\lim_{\eta \to 1} OVR_{wsdesign} = \left[\frac{Q}{D} - \left(\eta\frac{Q}{D} - \eta\frac{\Delta}{D_c}\right) - \frac{\Delta}{D_c}\right] = 0 \tag{A22}$$

In the surplus condition, using Eq. (A10), we obtain:

$$OVR_{wsdesign} = \left(\frac{Q}{D} - \eta\right) \cdot \left(1 - \frac{\Delta}{\left(\frac{Q}{D} - \eta\right) D \cdot n_{years}}\right) = \left(\frac{Q}{D} - \eta\right) \cdot (1 - k_{3,s}) \tag{A23}$$

and the aim is to neglect $k_{3,s}$ to obtain a simpler expression. The maximum value of $k_{3,s}$ is obtained for $\Delta = S$, and by considering S/D=0.09 and prudentially n_{years}=10, we obtain:

$$\max(k_{3,s}) = \frac{S}{\left(\frac{Q}{D} - \eta\right) D \cdot n_{years}} = \frac{0.009}{\left(\frac{Q}{D} - \eta\right)} = \frac{0.009}{(1-\eta)} \tag{A24}$$

where Q/D has been minimized to maximize $k_{3,s}$, that is, Q/D = 1 is considered. Hence, $k_{3,s} = k_{3,d}$ and the same considerations developed for $k_{3,d}$ apply for $k_{3,d}$.

Again, for η values close to 1, according to Eq. (A24), $k_{3,s}$ tends to infinity, and in order to overcome this discrepancy, the complete expression of $E_{ws,\ design}$, that is, Eq. (A8), is inserted into Eq. (A18) so that we obtain:

$$\lim_{\eta\to 1} OVR_{wsdesign} = \left(\frac{Q}{D} - \left(\eta - \eta\frac{\Delta}{D_c}\right) - \frac{\Delta}{\sum_{t=1}^{T} D_t}\right) = \frac{Q}{D} - 1 \tag{A25}$$

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