  Water Supply | 19.8 | 2019

Water efficiency and economic assessment of domestic rainwater harvesting systems in buildings with one- to three-floor elevations

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ABSTRACT

The focus of the paper is the evaluation of the performance of domestic rainwater harvesting (DRWH) systems in multi-family buildings with one- to three-floor elevations by means of a cost–benefit analysis. The rainwater is here used for both indoor and outdoor non-potable water consumption. The study was carried out with reference to different residential building typologies (flat and condominium) in a specific local climate condition (Ancona). The buildings are characterized by different rooftop areas (100–400 m^2), building floor elevations (one to three floors) and inhabitant numbers (3–54 persons). Moreover, in order to highlight the role of the tank capacity on the performance of DRWH, its capacity was changed in the range 50–200%. The combinations of all these parameters led to 276 test cases. The technical performance is evaluated by means of the water saving and retention efficiencies. The economical assessment is provided by comparing the costs and the savings due to the replacement of the water supplied with the rainwater. It is found that the payback periods changed in the range 10–35 years for the site-specific variables such as local rainfall and water service tariff. Cost–benefit analysis can help the design of DRWH systems, with particular attention to the sizing of the tank.

Key words | cash flows, domestic rainwater harvesting, payback period, water efficiency, water storage tank

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INTRODUCTION

The use of collected rainwater systems to support human non-potable consumption has been increasing in recent years. The primary reason for the use of domestic rainwater harvesting (DRWH) systems is potable water supply substitution (Mitchell *et al.* 2008). Pressure on water resources is increasing, with growing demand and limited water sources (Fletcher *et al.* 2008). This increasing demand reduces freshwater reservoirs (Sazakli *et al.* 2007) and it is followed by the use of lower quality sources (van Roon 2007). Therefore, in order to supply the amount of potable water, it is widely recognized that rainwater can replace it for several less quality-demanding water uses, such as house toilet flushing, car washing, terrace cleaning or private garden watering. A significant amount (up to 30%) of water in residential buildings (estimated currently to be 150 l/person per day) is typically used for toilet flushing, and about 22% for the washing machine (Eslamian 2016). The water demand for home garden irrigation is usually related to the square metres of the garden area, and indeed in the Italian guidelines UNI TS/11445–2012 an annual water demand for irrigation of 300 l/m^2 is reported.

However, water scarcity and need for water supply are not the only reasons that have led the municipality to boost RWH system installation. Farreny *et al.* (2011) provided a criterion for roof selection in order to maximize the availability and quality of rainwater from a perspective of

doi: 10.2166/ws.2019.124

sustainable rainwater management. In the last 20 years the literature shows that RWH belongs to the large family of detention-based Low Impact Development (LID) or Sustainable Drainage System (SuDS) approaches and can be adopted as a complementary measure to reduce frequency, peaks and volumes of urban runoff (Campisano *et al.* 2017). While water efficiency modelling approaches of RWH systems have been widely shown to give accurate representations when daily time-step intervals are used (e.g. Fewkes & Butler 2000; Campisano *et al.* 2013), accurate simulations of stormwater retention and runoff control should be made with higher resolution (sub-hourly time-steps) as suggested by Campisano & Modica (2015).

The need to address objectives that often mutually conflict, such as maximizing water saving and empty tank volume for runoff control with minimizing cost, requires customizing RWH systems in order to maximize their return on investment (Campisano *et al.* 2017).

The economic feasibility of a DRWH system depends on a lot of variables, such as rainfall climate regime, rooftop surfaces, inhabitant number and water service tariff, hence, different results can be obtained depending significantly on the local conditions (Ward *et al.* 2012). Tank storage capacity is commonly considered the most important cost in a DRWH system (e.g. Khastagir & Jayasuriya 2011; Ward *et al.* 2012). Pelak & Porporato (2016) evaluated the conditions of optimal cistern size as a function of rainfall regime as well as fixed and distributed costs under ideal operating conditions to provide a benchmark for further analysis of the impact of pricing policies and sustainability incentives on water consumption.

Life Cycle Cost (LCC) analysis is an economic analysis technique to estimate the total cost of a system over its life span. Within the LCC approach, the calculation of the Net Present Value (*NPV*) and the payback period were conducted (see the section on 'Economic assessment', below). In the literature, it was found that the payback period varied considerably, mainly due to the variation of tank size; Khastagir & Jayasuriya (2011) argued that unless the mains water price increases substantially (beyond $1.4/m^3), the rainwater tank user has to wait for 40 years to reach the payback period. Zhang *et al.* (2009) examined the financial availability of RWH systems in high-rise buildings in four capital cities in Australia, finding that the payback periods range from 10 to 21 years. Domènech & Saurí (2010) investigated the economic feasibility of the RWH system in single and multi-family buildings in Barcelona (Spain). An expected payback period was found to be between 33 and 43 years depending on the tank size in a single family building, while in a multi-family building a payback period of 61 years is obtained for a tank capacity of 20 m^3. Silva *et al.* (2015) found that the payback period can be in the range 15–30 years for a residential building with a collecting area of about 100 m^2 and a tank capacity of 0.2–2.0 m^3. Liuzzo *et al.* (2016) performed a cost–benefit analysis of DRWH in Sicily, finding payback periods in the range 15–38 years when both toilet flushing and irrigation uses were considered.

In the present paper, the evaluation of the payback period is based not only on the tank storage capacity but also on the pump size. Indeed, in specific cases such as a condominium with more than one floor elevation, the pump cost could be significant, due to higher head and, hence, larger size.

The main objective of the paper is to investigate the role of DRWH systems in multi-family buildings with one- to three-floor elevations in terms of both efficiency (see the section on 'Water efficiency', below) and payback period (see the section on 'Economic assessment', below) by means of a parametric analysis that takes into account different rooftop areas, building floors, inhabitant numbers and both tank capacity and, as a novel parameter, pump size. The cost–benefit analysis can provide useful help to the design of DRWH systems. Only direct benefits were considered in the present economic analysis.

MATERIALS AND METHODS

Test case description

The residential buildings were assumed to be located in Ancona, a town on the east coast of Italy, classified as a sub-coastal climate regime according to the Köppen–Geiger climate zoning map (Kottek *et al.* 2006). Rainfall data were provided by the rainfall gauging station of Ancona-Torrette, which has been operating since the year 1946. The precipitation data has been elaborated in order to identify the 'typical year', which corresponds to the year characterized by the minimum deviation of the observed data from those of the averaged year.

Different domestic building typologies were considered which were characterized by different rooftop area, number of floor elevations and inhabitant number. In order to study not only detached houses and to represent realistic and common building conditions for an Italian town, the number of floors was assumed to be in the range one to three (flat and condominium) and the rooftop area changed from 100 m^2 to 400 m^2. The inhabitant number was in the range 3–54. This value range has been obtained by following the Italian law about parameters for habitative and hygienic–sanitary suitability (D.M. 5/07/1975) which rules that for each inhabitant a minimum habitable surface must be ensured. Combinations of all these parameters have led to 45 different conditions. A garden surface of 50 m^2 for each family that lives at the ground floor (a family is assumed to be composed of three persons) is also considered in the simulations.

Water balance simulations were carried out choosing a daily time-step. In the present study the rainwater is used for both indoor (toilet flushing and washing machine) and outdoor (garden irrigation) non-potable consumption. The indoor water demand has been assumed to be equal to 50 l/person per day. The amount of irrigation demand is evaluated by considering a value of 5 l/m^2; this value is deduced by the typical value for the water demand for irrigation in Italian climatic conditions reported in Cavazza (1990). The garden irrigation demand is not equal during the year (needing about 100 days in a year), and it changes with the type of crops (Liuzzo *et al.* 2016). However, for simplicity, a constant water rate has been assumed by spreading the annual water irrigation demand over each day. Such simplification is also made by the Italian guidelines for the design of the rainwater harvesting system (UNI TS/11445–2012), in which the water demand for irrigation is assumed to be equal to a constant value.

In order to point out the significant role of the tank storage size *S*, evaluated by means of Equation (1), on the water efficiency and on the cost assessment, its capacity has been changed in the range 0.5*S*, 1.0*S*, 1.25*S*, 1.50*S*, 1.75*S*, 2*S* for each case, leading to a total number of test cases equal to 276 (only commercial tank sizes for underground installation were taken into account).

The reference tank capacity *S* has been evaluated as:

$$S = \min(D, R) \cdot \frac{n_D}{365} \tag{1}$$

where D is the water demand; R is the volume inflow $R = \varphi \eta A P$, given by the rainfall P, the rooftop area A, the runoff coefficient φ (set equal to 0.9) and another coefficient η (set equal to 0.9) to simulate the water loss due to filtering; n_{D} is the average yearly dry period (average consecutive non-rainy days in a year) which can be evaluated as:

$$n_{\mathrm{D}} = \frac{365 - n_{\mathrm{R}}}{12} \tag{2}$$

where n_{R} is the average number of yearly rainy days (or the number of rainy days in the typical year).

For the Italian guidelines UNI TS/11445–2012 there are two different ways to size the tank storage *S*: the simplified model (Equation (1) with $n_{\mathrm{D}}/365 = 0.06$) and the analytical model. The latter is based on the application of the mass balance equation for each time-step carried out by using the Yield After Spillage (YAS) operating rule (Fewkes & Butler 2000; Mitchell *et al.* 2008; Palla *et al.* 2011).

In Table 1 all the test cases analyzed in the present paper are summarized. Note that some test cases are characterized by the same rooftop surface *A* and number of inhabitants, but different numbers of building floors, thus the pump size, which is influenced by the head to be ensured at the draw-off points, changes. The pumps were sized by considering the design flow rate (which takes into consideration the probable simultaneous non-potable water demand) and the head. Submersible pumps characterized by a power of 0.37–2.20 kW were employed in the simulations.

Modelling and methodology analysis

The DRWH system is sketched by the rooftop surface, pipes, storage tank and distribution component which includes the pipes, the pump system and other devices that move water from storage to the point-of-use (see Figure 1). The hydrologic–hydraulic modelling is undertaken using EPA Storm Water Management Model (SWMM). The DRWH systems were simulated in SWMM as catchment area (rooftop surface), conduits, storage unit and pumping system.

Table 1 | Summary of the technical parameters of the test cases

Rooftop surface *A* (m^2)	Number of floors	Number of inhabitants	Number of families/floor	Tank capacity *S* (m^3)	Water demand *D* (m^3)
100	1	3	1	2, 3.75, 5.6, 6.5, 7.5, 8.5	81.3
	2	6	1	2, 3.75, 5.6, 6.5, 7.5, 8.5	138
	3	9	1	2, 3.75, 5.6, 6.5, 7.5, 8.5	194.7
150	1	3	1	2.5, 4.8, 7.5, 9.2, 12.75	81.3
	2	6	1	2.5, 5.6, 8.5, 9.6, 12.75	138
	3	9	1	2.5, 5.6, 8.5, 9.6, 12.75	194.7
	2	12	2	2.5, 5.6, 8.5, 9.6, 12.75	162.6
	3	18	2	2.5, 5.6, 8.5, 9.6, 12.75	276
200	1	6	2	3.75, 7.5, 8.5, 11.7, 12.75, 16	389.4
	2	12	2	3.75, 7.5, 8.5, 11.7, 12.75, 16	162.6
	1	9	3	3.75, 7.5, 8.5, 11.7, 12.75, 16	276
	2	18	3	3.75, 7.5, 8.5, 11.7, 12.75, 16	389.4
	3	27	3	3.75, 7.5, 8.5, 11.7, 12.75, 16	243.9
250	1	6	2	4.4, 9.2, 18.98, 12.75, 20, 16	414
	2	12	2	4.4, 9.6, 12.75, 16, 18.98, 20	584.1
	3	18	2	4.4, 9.6, 12.75, 16, 18.98, 20	162.6
	1	9	3	4.4, 9.6, 12.75, 16, 18.98, 20	276
	3	27	3	4.4, 9.6, 12.75, 16, 18.98, 20	389.4
300	1	6	2	4.4, 9.2, 20, 12.75, 25.2, 16, 26	243.9
	2	12	2	5.6, 11.7, 12.75, 16, 20, 25.2, 26	414
	3	18	2	5.6, 11.7, 12.75, 16, 20, 25.2, 26	584.1
	1	9	3	5.6, 11.7, 12.75, 16, 20, 25.2, 26	162.6
	3	27	3	5.6, 11.7, 12.75, 16, 20, 25.2, 26	276
	2	24	4	5.6, 11.7, 12.75, 16, 20, 25.2, 26	389.4
	3	36	4	5.6, 11.7, 12.75, 16, 20, 25.2, 26	243.9
350	1	9	3	8.5, 16, 20, 25.2, 31.42	414
	2	18	3	8.5, 16, 20, 25.2, 31.42	584.1
	3	27	3	8.5, 16, 20, 25.2, 31.42	325.2
	1	12	4	8.5, 16, 20, 25.2, 31.42	552
	2	24	4	8.5, 16, 20, 25.2, 31.42	778.8
	3	36	4	8.5, 16, 20, 25.2, 31.42	243.9
	1	15	5	8.5, 16, 20, 25.2, 31.42	414
	2	30	5	8.5, 16, 20, 25.2, 31.42	584.1
	3	45	5	8.5, 16, 20, 25.2, 31.42	325.2
400	1	9	3	8.5, 16, 20, 25.2, 31.42, 37.65, 40	552
	2	18	3	8.5, 16, 20, 25.2, 31.42, 37.65, 40	778.8
	3	27	3	8.5, 16, 20, 25.2, 31.42, 37.65, 40	406.5
	1	12	4	8.5, 16, 20, 25.2, 31.42, 37.65, 40	690
	2	24	4	8.5, 16, 20, 25.2, 31.42, 37.65, 40	973.5
	3	36	4	8.5, 16, 20, 25.2, 31.42, 37.65, 40	243.9
	1	15	5	8.5, 16, 20, 25.2, 31.42, 37.65, 40	414
	2	30	5	8.5, 16, 20, 25.2, 31.42, 37.65, 40	584.1
	3	45	5	8.5, 16, 20, 25.2, 31.42, 37.65, 40	325.2
	2	36	6	8.5, 16, 20, 25.2, 31.42, 37.65, 40	552
	3	54	6	8.5, 16, 20, 25.2, 31.42, 37.65, 40	778.8

The commercial tanks were described in the model by using the storage curve (tabular function). The pump operating data were included by using the pump curve (head vs flow rate) from which, knowing the head of each test case, the operating flow rate is obtained. Two control rules were used for the pumping systems in order to simulate the operating of the pump: (i) when the rainwater level into the tank (inlet node) is larger than its dead-head condition

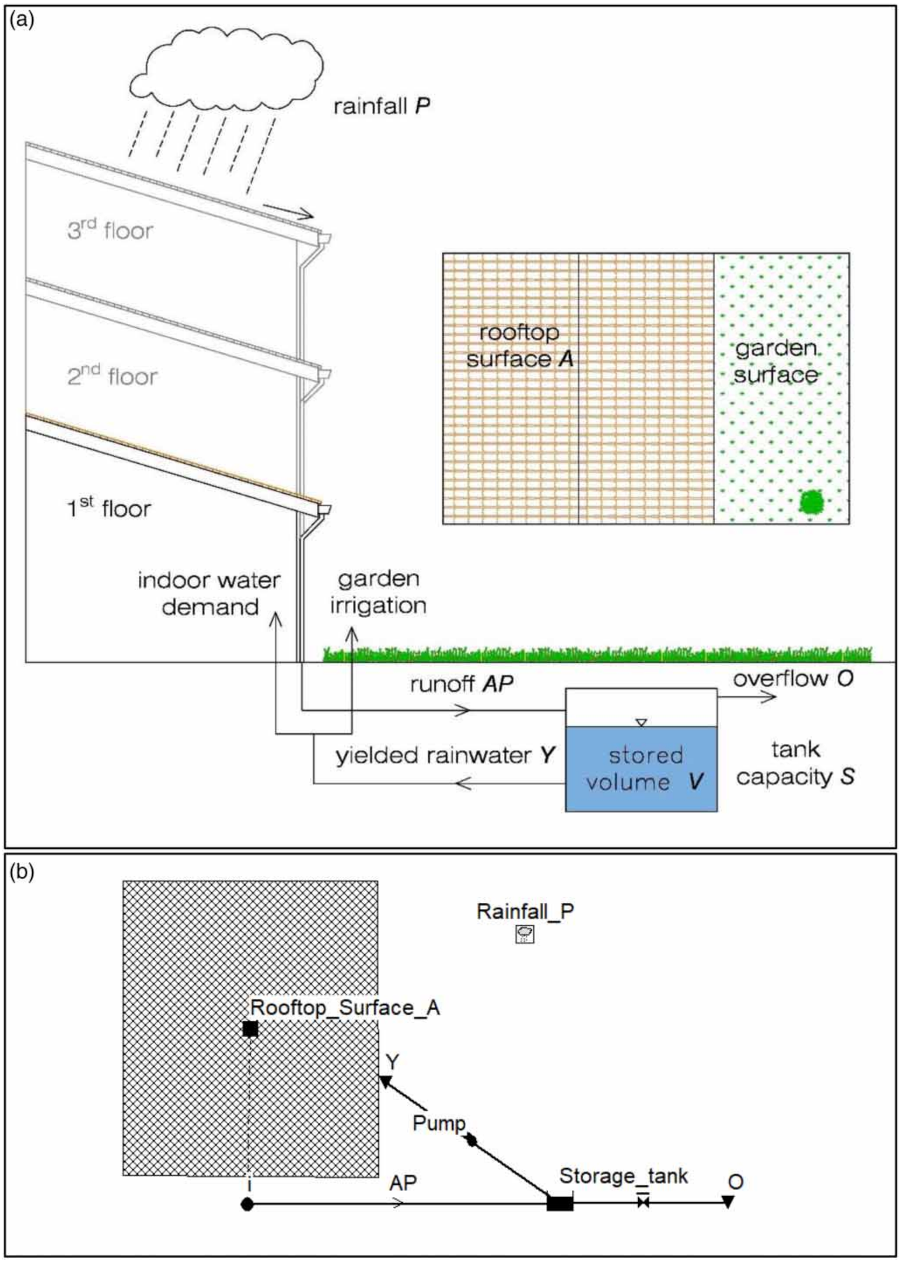

Figure 1 | (a) Sketch of the hydraulic balance of a DRWH system; (b) Scheme of a DRWH system in SWMM.

and (ii) for a time period needed to pump the daily water demand D_t to the outlet node (this time is evaluated by dividing the daily water demand with the operational flow rate). Moreover, an additional outfall (free boundary conditions) simulates the overflow discharged into sewer piping.

Tank water saving efficiency E_{WS} (%) and tank volumetric retention efficiency E_R (%) were here defined as proposed by Campisano & Modica (2015):

$$E_{WS} = \frac{\sum Y_t}{\sum D_t} \tag{3}$$

$$E_R = 1 - \frac{\sum O_t}{\sum AP_t} \tag{4}$$

where Y_t is the volume of rainwater yielded from the storage tank at time step t (in the present study t corresponds to one day), D_t is the non-potable water demand at time step t, O_t is the volume discharged as overflow from the storage tank at time step t, P_t is the precipitation of the 'typical year' at time step t and A is the rooftop surface, (the term AP_t is the runoff when the water loss is null). In Figure 1(a) scheme of the DRWH system is reported, where V is the volume stored in the tank.

WATER EFFICIENCY

Rainfall analysis

The rainfall analysis is based on the rainfall data provided by the 'Dipartimento di Protezione Civile' of the Marche region for the rainfall gauging station of Ancona-Torrette. These data were analyzed in the period 1951–2013 for the design of the drainage piping systems. To evaluate the behaviour of the DRHW system in real conditions, a real hyetograph is used based on the daily precipitation of the 'typical year'. The average year is calculated with reference to the monthly precipitation data in the period 1990–2013. The deviations $\sigma_{m,i}$ (the subscript i and m referring, respectively, to the year and the month analyzed) were calculated referring to the monthly precipitation $P_{m,i}$ of each year with respect to the corresponding monthly value $\overline{P_{m,i}}$ of the average year:

$$\sigma_{m,i} = (P_{m,i} - \overline{P_{m,i}}) \quad (5)$$

For each year the squares of the monthly deviations were added: $\sum_{m=1}^{12} \sigma^2_{m,i}$. The typical year was identified as the year with the minimum value of $\sum_{m=1}^{12} \sigma^2_{m,i}$.

The cumulative annual precipitation varies in the range 382–1,192 mm, as can be observed in Figure 2(a). Figure 2(a) also shows the trend of the variance in the observed period 1990–2013. The minimum value of $\sum_{m=1}^{12} \sigma^2_{m,i}$ is obtained for the year 1998, thus, that year has been identified as the typical year.

The dashed line in Figure 2(a) represents the yearly precipitation of the average year, which is equal to 718 mm. The cumulative annual precipitation of the typical year is, instead, equal to 634 mm, hence it is lower than the average value. Such a difference does not affect the goodness of the results, because the performance of the DRWH depends on the evolution of the precipitation through the year, characteristic of the site climate conditions, and not on the cumulative yearly value. Moreover, the evaluation of the water saving efficiency based on the rainfall data of a year characterized by a lower value of annual precipitation with respect to that of the average year surely provides a cautionary result in terms of water saving efficiency. The average value of the yearly rainy days in the period 1990–2013 is equal to 68 days, while in 1998 (the typical year) the number of rainy days was equal to 60. The use of the multi-year rainfall data set was made only for some representative study cases corresponding to the maximum number of inhabitants of each rooftop surface considered in the present study. Such multi-year simulations gave similar results, confirming that the use of a more concise rainfall data set, as that of the 'typical year', can well represent the climate conditions of the site, and hence the hydraulic behaviour of the DRWH systems.

Figure 2(b) shows the comparison of both the monthly precipitation and rainy days between the average and the typical year. The typical year trends show more evident variations over the months with respect to those of the average year, for which the smoothing is just due to the average operations. Therefore, the typical year is confirmed to be more representative of the hydrologic characteristic of the site with respect to the average year, with longer dry/wet periods and more pronounced peaks/troughs.

Water efficiency

In the present section the results of the simulations were analyzed in order to evaluate the water saving efficiency expressed by Equation (3) and the water retention efficiency defined by Equation (4).

To consider different combinations of water demand D, storage capacity S, rooftop area A and annual precipitation P, two dimensionless ratios are traditionally taken into account in the literature, namely demand fraction $d = D/AP$ and storage fraction $s = S/AP$.

In Figure 3 the numerical results for the temporal evolution of the water balance are shown for the test cases

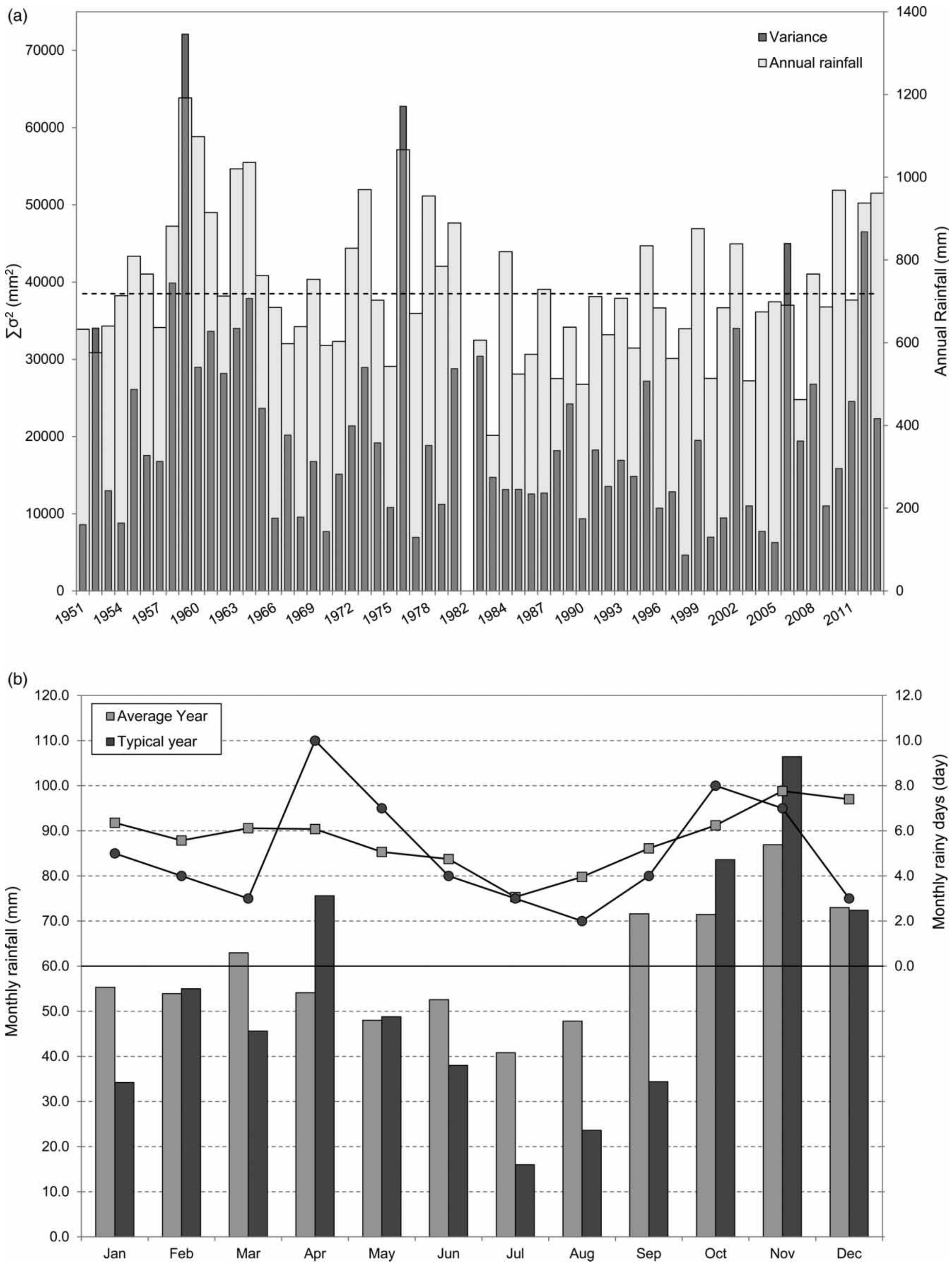

Figure 2 | (a) Annual cumulative rainfall (light gray) and variance (dark gray) in the period 1951–2013; (b) comparison of the monthly rainfall and rainy days between the average year (square, light gray) and the typical year (circle, dark gray). Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/ws.2019.124.

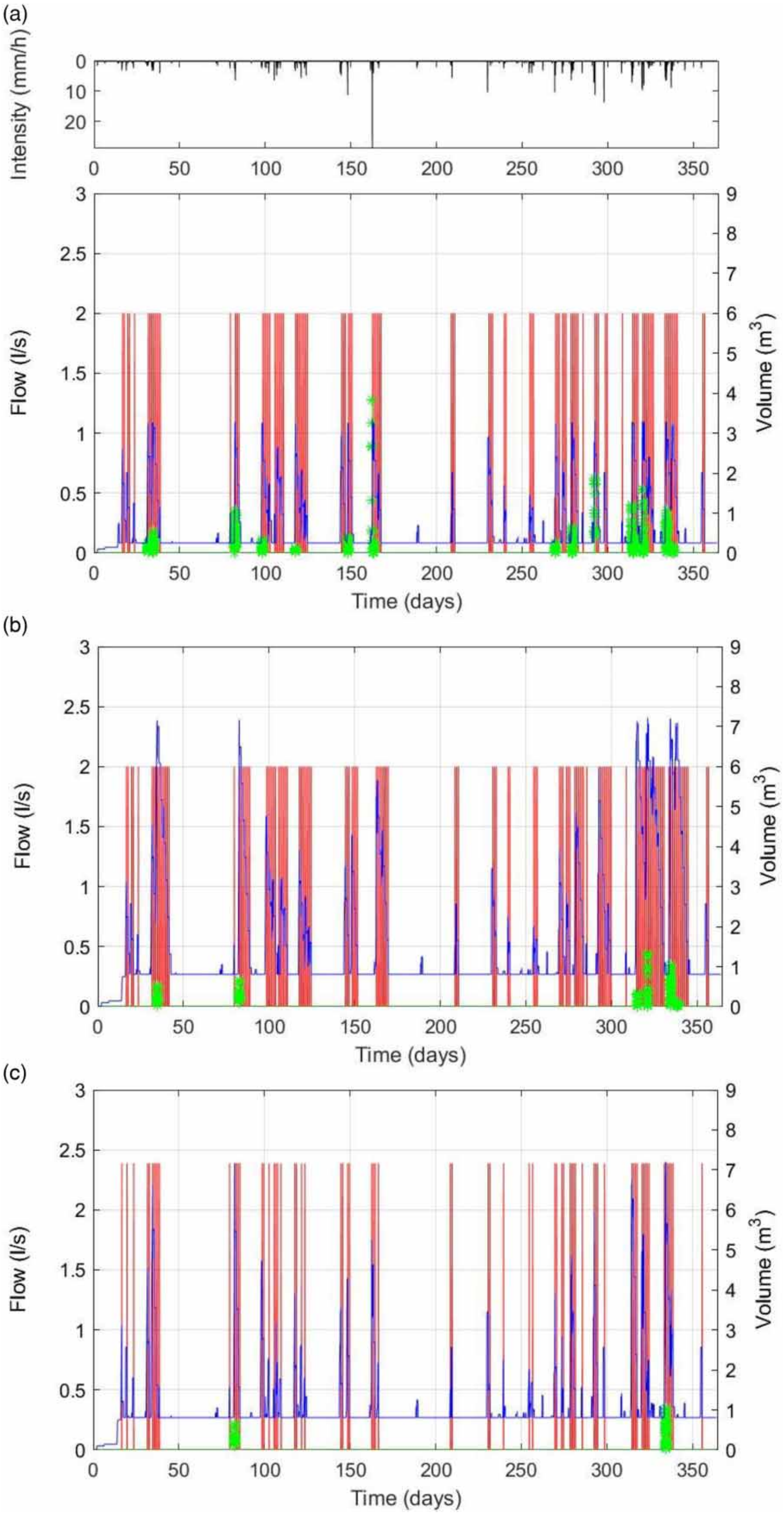

Figure 3 | Rainfall intensity (black line); harvested water volume (blue line), pumped water flow (red line), overflow (green asterisk) for the test case with a rooftop surface $A = 200$ m^2: 12 inhabitants, water demand fraction $d = 1.99$, storage fraction $s = 0.027$ (a) and $s = 0.054$ (b); 27 inhabitants, water demand fraction $d = 4.22$ and $s = 0.054$ (c). Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/ws.2019.124.

with rooftop surface $A = 200\ m^2$ and different water demands and storage fractions. Figure 3(a) and 3(b) show the water balance results for the cases of 12 inhabitants, water demand fraction $d = 1.99$ and two different storage fractions: $s = 0.027$ and $s = 0.054$; while Figure 3(c) shows the case of 27 inhabitants, water demand fraction $d = 4.22$ and storage fraction $s = 0.054$.

Inspection of Figure 3 reveals that the increase of tank storage capacity allows the increase of water yielded from the tank storage, hence, the pumped water flow (red lines) becomes larger. At the same time the overflow (green asterisks) decreases due to the larger storage capacity. Figure 3(b) and 3(c) also reveal that with the increase of the demand fraction d, the frequency of the pump activation (red line) decreases, hence, the yielded water also decreases. Therefore, for the same rainfall regime, the decrease of the available water within the same tank storage capacity occurs for the test cases with a larger water demand (greater number of people).

Figure 4(a) shows the influence of the water demand fraction d and storage fraction s on the water saving efficiency E_{WS} defined in Equation (3). For all the test cases here analyzed, the water saving efficiency E_{WS} ranges from 20% to 80%. By employing the multi-year rainfall data, a slight increase of E_{WS} with, at the same time, a slight decrease of d is observed (this behaviour is due to a larger value of the average annual rainfall). The validity of the results obtained by using the 'typical year' is proved by the observation (here not reported) that the multi-year results overlap those of Figure 4, confirming that the 'typical year' is representative of the local climate conditions and it can well reproduce the performance of DRWH systems in the specific local site.

Figure 4(a) reveals also that the influence of the storage capacity on the water saving efficiency becomes ever smaller with the increase of the demand fraction. Larger efficiency can be achieved with both small demand fraction (small water demand, significant rainfall regime or wide rooftop surface) and large tank storage capacity. In the latter case it is very important to evaluate not only the efficiency of a DRWH, but also its economic feasibility, as reported in the next section, the tank cost being significant for the investment.

It is found that the water saving efficiency E_{WS} is a function of the water demand fraction $d = D/AP$ with the following expression:

$$E_{WS} = a \cdot d^b \qquad (6)$$

where a and b are coefficients that depend on both the tank storage fraction and the rainfall regime. The best-fit laws were obtained for three different tank storage fractions ($s < 0.05$, $0.05 \leq s < 0.09$ and $s \geq 0.09$) with a very good determination coefficient R^2. It is observed that the exponent b is almost the same ($b \approx -0.8$) for the different ranges of the tank storage fraction, hence, it seems dependent only on the rainfall regime (the small discrepancy is only due to the nature of the experimental data), while the coefficient a increases with the tank storage capacity: $a = 65$ for tank storage fraction $s < 0.05$ ($R^2 = 0.96$); $a = 80$ for $0.05 \leq s < 0.09$ ($R^2 = 0.98$) and $a = 87$ for $s \geq 0.09$ ($R^2 = 0.98$). Such results are in agreement with those of Sanches Fernandes *et al.* (2015) who found that for demand fractions $d > 0.8$ the water saving efficiency shows a marked dependency on the water demand, fitting with a power function.

By analysing the results of the simulations for all the test cases, the volume retention efficiency E_R, defined in Equation (4), ranges from 60% to 100% (see Figure 4(b)). A very good retention efficiency is achieved for almost all the test cases with the demand fraction d larger than 2. The maximum value of the retention efficiency (100%) is obtained for storage fraction $s \geq 0.09$. This result suggests that the use of large tank storage capacity ($s \geq 0.09$) could be unnecessary in terms of water savings, and, in addition, it implies a more significant investment. However, these conditions ($s \geq 0.09$) can be adopted when the DRWH is used as a system for stormwater runoff control.

ECONOMIC ASSESSMENT

The economic assessment was based on the cost and saving flows by considering the future prediction of the costs along the design life span, in order to evaluate the payback period for each different test case. The capital costs are due to the tank, pipes, pump (influenced by the number of inhabitants and floor elevations), devices, installation, and maintenance, while the savings are due to water replacement, which is the primary benefit of such a system. The actual water

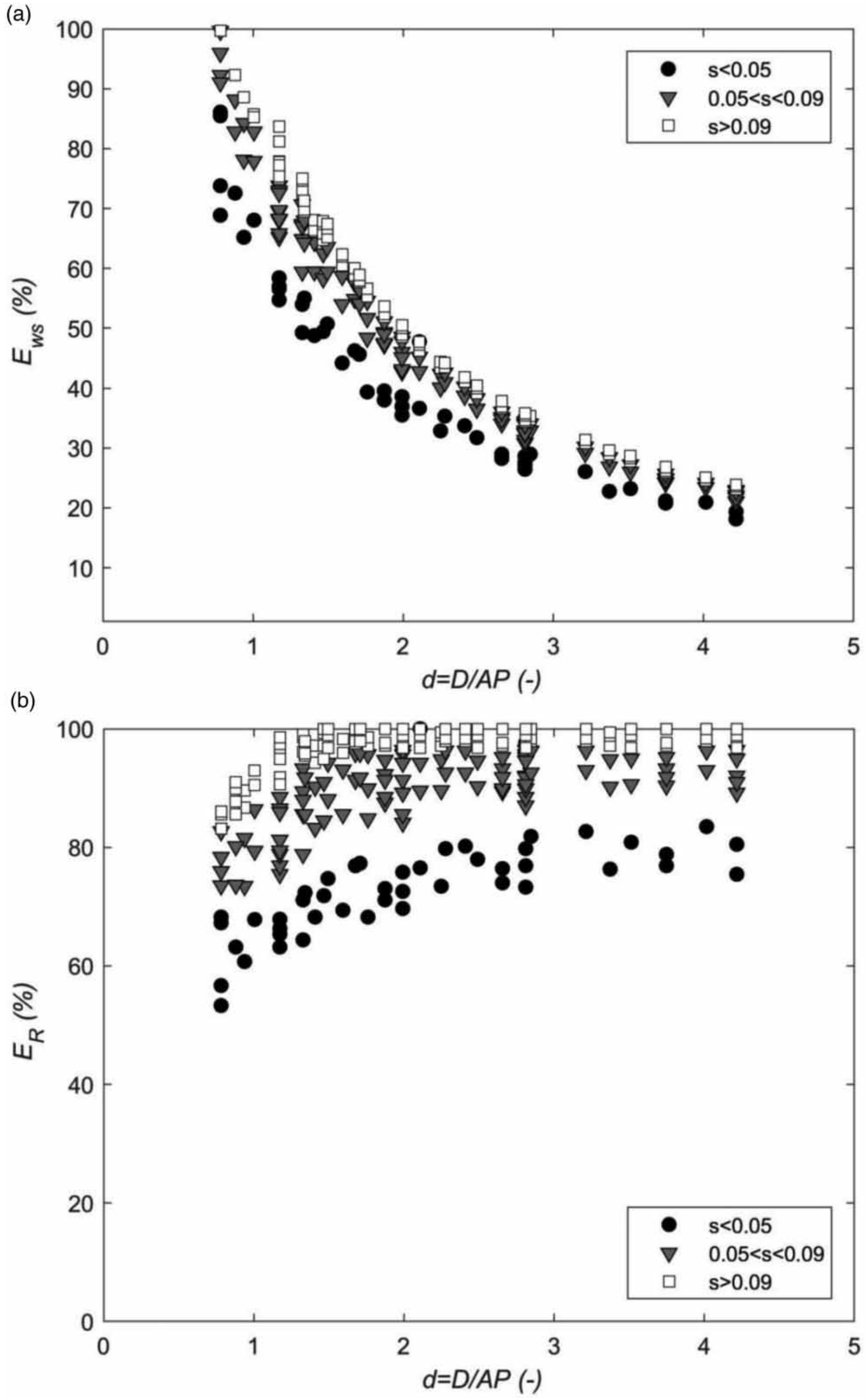

Figure 4 | Influence of the water demand fraction $d = D/AP$ and storage fraction $s = S/AP$ on: (a) the water saving efficiency and (b) the water retention efficiency.

service tariff in Ancona is about 2.3€/m^3 (by assuming a water consumption for a family within the range 121–180 m^3 per year). In the economic analysis the water service tariff (composed of the fixed charges, water cost, and sewer and wastewater treatment costs) is a key factor, with savings for cost of water supplied by the rainwater. The variation with time of the water cost, sewer and wastewater treatment tariffs for the town of Ancona presents different trends.

Predictions about future water service tariff through the design life-span are taken into account by means of a linear trend of each component of the water service tariff (+6.9% for the water cost, +2.9% for the sewer and wastewater treatment costs). The economic analysis also includes a constant annual increase in the energy prices (+0.7%). Such predictions will be used for the evaluation of the payback period.

The NPV is the difference between the present value of cash inflows and cash outflows over a period of time of the investment, and can be expressed as:

$$NPV = -C_C + \sum_{n=0}^{N} \frac{CW - C_{YWM} - CE - C_M}{(1+r)^n} \quad (7)$$

where C_c is the capital cost, CW is the cost of water demand D, C_M is the maintenance cost, C_{YWM} is the cost of water supplied by the mains $D-Y$, CE is the cost of electricity for the pump, r is the discount rate, N is the design life period, and n is the length of time since the investment.

The main term of the capital cost C_c is given by the tank cost. The storage capacity used in the simulations (2–40 m^3) results from the technical data given by different companies for plastic tanks. For such storage capacities the tank costs are in the range 1,200€–25,000€. The pump costs are in the range 400€–1,000€. For each test case the number of pump start-ups and, hence, the hours of pump usage were provided by the simulations. Knowing the power consumption and the electricity tariff, the energy costs needed to pump the rainwater were evaluated. The other costs for the devices, piping systems, and filter were considered in the range 800€–2,000€. The maintenance cost C_M was assumed to be equal to 10% of the capital cost C_c.

As above reported, the main savings are due to water replacement. With the water service tariff in Italy being lower than those of other European countries, a positive NPV can be obtained only after a long time from the investment. Indeed, in the literature the payback periods are longer than 10 years. It is difficult to predict future interest and inflation rates due to wide fluctuations in the economy. Therefore, in the present study, the discount rate r has been assumed equal to zero, prediction of future interest and inflation rates being too uncertain due to wide fluctuation in the economy over so long a time period.

The payback period is defined as the length of time required to obtain a profit from the investment, hence, it is equal to the time period when the NPV becomes positive ($NPV > 0$).

Figure 5 shows that the payback periods changed in the range 10–35 years for the site-specific variables such as local rainfall and water service tariff. A very weak influence of the demand fraction on the payback period has been found, while, as expected, the payback period is strongly influenced by the storage fraction. Note that in the economic computations other costs also have been taken into account: it was found that the pump costs became significant in the case of buildings with two or three floors and a large number of people. Indeed, the pump cost can be about

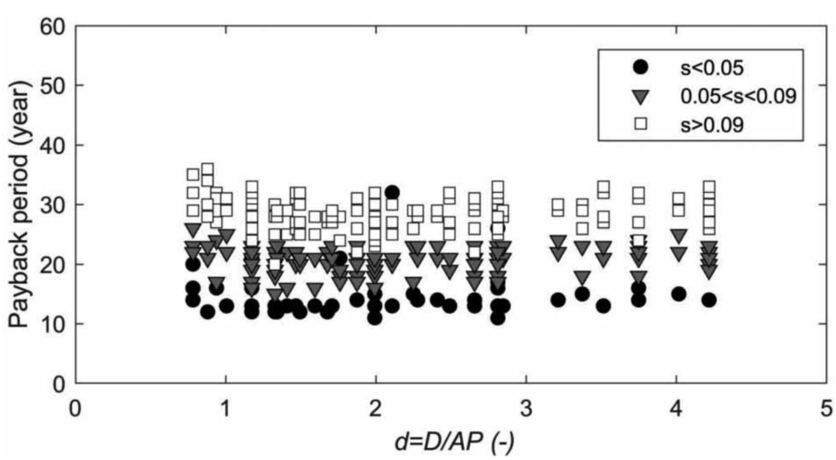

Figure 5 | Influence of the payback period on the water demand fraction d and storage fraction $s = S/AP$.

20% of the tank cost for a building with a rooftop area $\leq 200\ m^2$ with three floors and a storage fraction $s < 0.05$. However, when only the influence of tank storage size on the payback period is considered, twice the tank storage capacity led to an increase of the payback periods of about 20–30%. Payback periods of less than 20 years can be obtained only with tank storage fractions $s < 0.05$.

CONCLUSIONS

Several simulations of the performance of domestic rainwater systems were carried out in order to analyze both the efficiencies and the payback period of different residential building typologies. The analysis was performed in order to consider the combination of different parameters such as the rooftop surface, building floor elevations, inhabitant number, water demand, tank capacity and pump size. Only the possible combinations of rooftop surface, number of floors and inhabitants that represent real test cases have been considered in the study. Moreover, only commercial tanks and pumps have been considered in the analysis. The influences of pump cost and of energy consumption, usually neglected, were here investigated. The tank size is certainly the most important cost in a DRWH system investment, however, in a building with more than one floor, the pump cost could be significant, leading to about 20% of the tank cost for buildings with three floors and a storage fraction lower than 0.05, and in particular a value of 30% of the tank cost was obtained for a building with three floors and a rooftop area of 100–150 m^2. However, the increase of the rooftop surface influences the sizing of the tank (becoming larger), and consequently the tank cost becomes the dominant term in the investment. The water saving efficiency is in the range 20–80% and it increases in the cases of small water demand fraction. A best-fit law is obtained for the water saving efficiency and the water demand for three different storage capacity fractions. An increase of tank storage size of 100% leads to an increase of efficiency of about 10–20%, but, at the same time, a significant increase (about 20–30%) of the payback period. Payback periods lower than 20 years were obtained only when the storage fraction $s < 0.05$. The parametric analysis on the influence of the tank capacity (which is varied in the range 50–200% with respect to that evaluated by Equation (1)) reveals that the DRWH system would be economically feasible when $s < 0.05$ and, approximately, when the tank S is less than about 12 m^3 (the storage capacity used in the simulations is in the range 2–40 m^3). This condition is almost verified when Equation (1) is applied. Therefore, the cost–benefit analysis can help the designer to optimize the size of the tank from an economic point of view. An oversized tank is disadvantageous, because the increase in water efficiency, due to the increase of the yielded rainwater, is not balanced by a significant increase in savings due to water replacement, the Italian water service tariff being low. However, such a solution can be adopted when the DRWH is used as a system for stormwater runoff control. In conclusion, a parametric estimation of DRWH system performance (both technical and economical) has been achieved for buildings in a specific local site of sub-coastal Italian climate regime (Ancona). The extension of the payback period results to other site conditions should be verified and made with care due to the significant influence of both the local climate conditions and the local water service tariff on the feasibility of the DRWH systems.

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First received 28 April 2019; accepted in revised form 21 August 2019. Available online 3 September 2019