Rainwater harvesting as source control option to reduce roof runoff peaks to downstream drainage systems

Alberto Campisano and Carlo Modica

ABSTRACT

The objective of the paper is to evaluate the potential of tank-based rainwater harvesting systems in free standing houses as the source control method to mitigate peak roof runoff due to rainfall in urban areas. To this aim, the water balance simulation of the rainwater tank was carried out using both high resolution rainfall series and toilet water demand data extracted from the database of results built in a previous field campaign involving six experimental households in southern Italy. Simulations show that significant potential for runoff peak reduction exists, basically depending on the rainwater tank size and on the characteristics of the water demand in the house.

Key words | rainwater harvesting, rainwater tanks, runoff peak control, sustainable urban drainage systems (SUDS)

Alberto Campisano (corresponding author)
Carlo Modica
Department of Civil Engineering and Architecture,
University of Catania,
Viale A. Doria 6,
95125 Catania,
Italy
E-mail: *acampisa@dica.unict.it*

LIST OF SYMBOLS

A	effective impervious area of the rooftop [m^2]
A_{tot}	total rooftop area [m^2]
d	demand fraction [–]
D_d	average daily toilet water demand [m^3]
D_t	toilet water demand at time t [m^3]
E_{PR}	peak retention efficiency [%]
φ	rooftop runoff coefficient [–]
$Q_{D\mathrm{peak}}$	volume discharged as overflow from the storage tank at peak time [m^3]
Q_{Dt}	tank overflow discharge volume at time t [m^3]
Q_t	inflow volume to the tank at time step t [m^3]
R_d	average daily rainfall [m^3]
R_{peak}	rainfall at peak time [m]
R_t	collected rainfall at time step t [m]
S	tank storage capacity [m^3]
s	storage fraction [–]
t	time step [s]
Y_t	yielded volume of rainwater from the storage tank at time t [m^3]

INTRODUCTION

For centuries, rainwater has been harvested and stored in cisterns and tanks to support human water use. Recently, especially in the context of urban settlements, systems for domestic rainwater harvesting (RWH) have been gaining impetus in both developed and developing countries as a complementary supply source to save fresh water (Cook *et al.* 2013).

Implementation of RWH systems in buildings normally requires setting up tanks of appropriate size to store rainwater collected from rooftops or terraces. Once subjected to treatment to eliminate pathogens and heavy metals, stored rainwater is used locally for both internal and external non-potable consumption (i.e., toilet flushing, garden irrigation, terrace cleaning, etc.).

Several studies have been carried out in various countries over the years to analyze the performance of rain water tanks in free standing houses (Chilton *et al.* 1999; Zaizen *et al.* 1999; Glist 2005; Kus *et al.* 2011; Ward *et al.* 2012). Many of them took into consideration the

doi: 10.2166/hydro.2015.133

house indoor rainwater demand for toilet flushing since, in most of the cases, this demand represents a very important component of the household water consumption and does not necessarily require high water quality requisites.

Existing studies agree in indicating that RWH systems may provide a relatively high performance in terms of water saving (saved fresh water from mains in the house). However, performance is markedly influenced by site-specific variables, i.e., the local rainfall pattern, the roof type and surface area, the tank size, the demand for rainwater, the number of people belonging to the household, etc.

At the same time, in several cases, rainwater tanks have been recognized also as a method to mitigate environmental impacts of urbanization on stormwater drainage systems and receiving water bodies (Zhang *et al.* 2012; Burns *et al.* 2014; Campisano & Modica 2015). The extensive implementation of rainwater tanks throughout urban catchments may significantly increase their diffuse retention potential and help in reducing frequency, volume and peaks of stormwater runoff conveyed into the urban drainage network (Gerolin *et al.* 2010; Petrucci *et al.* 2012; Burns *et al.* 2014). Specifically, RWH operates as a storage-based source control solution: during rain events, part of the rainfall is intercepted and stored by the rainwater tank with the effect of reducing the surface runoff component. Differently from traditional stormwater tanks, the size of RWH tanks is normally much smaller and also the obtained water abstraction is demand-driven (Petrucci *et al.* 2012) with demand magnitude and patterns affecting the tank design and efficiency (Mitchell *et al.* 2008).

Multiple benefits of RWH tanks have been numerically analyzed by many researchers based on the long-term water balance simulation of the tank (Ghisi & Ferreira 2007; Mitchell *et al.* 2007; Brodie 2012; Campisano & Modica 2012; Campisano *et al.* 2014). Simulation schemes used for such analyses are normally based on considering rainfall and household water demand as tank inflow and outflow, respectively.

Very recently, Campisano & Modica (2015) have investigated how the model setup may affect the results of the simulations (and then the correct estimation of the tank design/reliability) with specific reference to the proper resolution time scale to adopt for simulations. Results of the investigation show that the daily time step resolution can be properly adopted for a correct evaluation of the RWH system water saving performance. However, increased simulation time resolution (at least the hourly time scale) is required if the aim of the analysis is to evaluate the tank potential to reduce runoff volumes to the downstream stormwater drainage system.

The evaluation of the retention potential of rainwater tanks to reduce peak roof runoff is the objective of the present paper. The evaluation required increasing the temporal resolution of the analysis through the adoption of very small time steps for rainfall data acquisition, for water demand estimation, and for model simulations. Then, increased computational efforts were sustained, notably due to the need of treating extended rainfall data sets and to set up appropriate methods to decompose water demand data that are normally available as aggregated records.

Data regarding water consumption recorded at six pilot households in the south of Italy acquired during a previous field monitoring campaign (Campisano & Modica 2010) were considered for the present study. The procedure by Campisano & Modica (2015) was customized for appropriate downscaling of field observed data in order to derive synthetic series of water demands at the toilet at the resolution time scale of 1 minute. The obtained water demand series, together with the rainfall data series at the same time scale, were used to simulate the tank water balance and to evaluate the reduction of the roof runoff peak potentially conveyed to the downstream system. A dimensionless approach was adopted for the generalization of the results and a novel parameter indicator was proposed to measure the tank efficiency to reduce the runoff peak.

METHODS

The RWH system scheme considered for the analysis is shown in Figure 1. The scheme provides for the collection of rainwater falling on the building roof. The rainwater is temporarily stored within the rainwater tank that is equipped with a dedicated piping system (disconnected from the mains) allowing the supply of rainwater to the toilet cistern. The toilet is assumed to use primarily the water accumulated into the rainwater tank, i.e., the water from the mains is sourced to the toilet only in the case that the tank is empty.

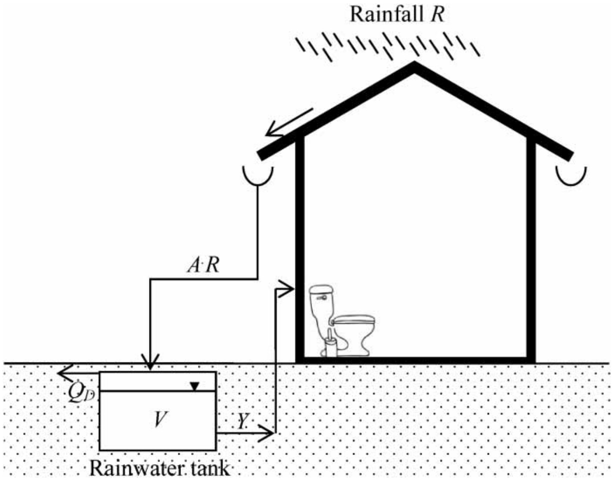

Figure 1 | Schematic of the domestic rainwater harvesting system. R is the rainfall, A is the effective rooftop area for rainwater collection, Y is the yield from the rainwater tank, Q_D is the overflow, V is the volume in store.

The procedure adopted for simulations consists of three basic steps aimed: (1) at evaluating the rainwater inflow to the tank; (2) at estimating the house rainwater demand pattern; and (3) at simulating the tank water balance.

Inflow to the tank

As for the evaluation of the inflow, the tank is considered to be filled exclusively by the rainwater which falls on the rooftop of the building. Assuming the rainfall to be constant within each computational time interval t (equal to 1 minute for this analysis) and neglecting the lag effect due to rainfall–runoff transformation over the roof, the volume of rainwater conveyed to the tank is calculated as:

$$Q_t = \varphi \cdot R_t \cdot A_{\text{tot}} = R_t \cdot A \tag{1}$$

where Q_t [m^3] is the inflow volume supplied to the tank at time step t; φ[-] is the runoff coefficient; A_{tot} [m^2] is the total rooftop area for rainwater collection connected to the tank; $A = \varphi \cdot A_{\text{tot}}$ [m^2] is the effective impervious area of the rooftop; and R_t [m] is the collected rainfall at time step t.

Tank outflow due to toilet demand

The two-phase procedure by Campisano & Modica (2015) was here customized to determine toilet demand series at a 1-minute time step for the analysis of peak runoff reduction. In the first phase, the series of daily demands for toilet flushing over the year is generated, i.e., the number of daily toilet flushes (per capita) occurring in the house during each of the 365 days of the year. To this aim, data on the users' habits concerning both the daily frequency of toilet use and the number of users present at each of the six houses during the day are examined. In particular, total flushes occurring during each day of the monitoring period are obtained, and daily per capita toilet flushes are calculated based on the user presence at home. A normal cumulative distribution function (CDF) is fitted to obtained values. The CDF is assumed to represent the toilet use daily pattern for the whole year (here referred to as the daily demand pattern). Then, random selection by the CDF is used to generate the synthetic series of 365 daily values of (per capita) toilet flushes for all the days of the year. To evaluate the total daily number of flushes in the house, the obtained values are multiplied for the daily number of household users.

The second phase of the procedure allows for scaling the toilet use daily pattern down to the 1-minute time step resolution. The procedure allows the 1-minute sub-hourly pattern of the toilet use frequency starting from the observed daily pattern to be defined. In particular, for the required time scale, each day of the period of observation was analyzed separately and each monitored flush event was labeled according to its time of occurrence (hour and minute) in the day. Flushes during the day are then chronologically aggregated using a 1-minute time interval. Then, the procedure by Campisano & Modica (2015) was adopted which required the 'overlap' of the obtained daily chronological series of aggregated flushes (one for each of the days of the monitoring period) in order to cumulate flushes falling within the same minute time step of the various days. Data are then normalized to the total number of flushes observed during the whole monitoring period and a cumulated relative frequency distribution of the toilet use during the day at the selected scale is obtained. Random picks (in number equal to the household daily flushes resulting from phase one) are finally sampled out by the cumulated frequency distribution to determine the daytime minute to be assigned to each flush. The procedure is arrested when the complete synthetic series of toilet flushes (over the whole year) is generated.

Water balances

The method used to track the tank water balance is based on the yield-after-spillage algorithm as tank release rule (Jenkins *et al.* 1978). This algorithm is simple to implement and it has been widely used in the literature to evaluate RWH system performance under a large spectrum of conditions.

To evaluate properly the performance of the tank to reduce roof runoff peaks conveyed to the downstream drainage system, a new parameter of tank efficiency is introduced:

$$E_{\mathrm{PR}} = \left[1 - \frac{Q_{D\,\mathrm{peak}}}{A \cdot R_{\mathrm{peak}}}\right] \cdot 100 \tag{2}$$

where $Q_{D\,\mathrm{peak}}$ [m^3] and R_{peak} [m] are the volume discharged as overflow from the storage tank and the rainfall at respective peak times. Equation (2) shows E_{PR} [%] to provide a measure of how much the storage tank is able to reduce/retain the runoff peak associated with the precipitation event. E_{PR} is evaluated separately for each individual event of the simulation.

To produce results that may be used for more general evaluations, the tank efficiency was explored by following a non-dimensional approach. In particular, two dimensionless parameters, namely, the demand fraction d and the storage fraction s have been taken into account:

$$d = \frac{D_d}{A \cdot R_d}; \quad s = \frac{S}{A \cdot R_d} \tag{3}$$

with D_d and R_d being the average (in the year) daily values of toilet water demand and rainfall, respectively, and S [m^3] being the tank size (storage capacity).

The use of such parameters provided the simulations to take into account different scenarios characterized by several combinations of tank storage capacity, collecting roof area, rain water demand, and precipitation (Fewkes & Butler 2000).

Values of d and s for model simulations were selected based on the range of values that dimensional variables D_d, R_d, A, and S assume in the practical application. In particular, according to Fewkes & Butler (2000), various demand and storage scenarios were considered. Four values of demand fraction ($d = 0.5$; $d = 1.0$; $d = 2.0$; $d = 4.0$) were assumed while six values of storage fraction were used, with s equal to 1, 2, 3, 5, 10, and 20, respectively.

In principle, as d and s are defined at the daily scale (i.e., D_d and R_d are daily values), the selection of their value is irrespective of water demand and rainfall temporal distribution during the day. The influence of such distribution was taken into account directly at the time that detailed rainfall and water demand patterns were used for the water balance simulation of the tank.

For the evaluation of E_{PR} from simulations, the rainfall events were assumed to be independent if they showed a minimum antecedent dry weather period of 1 hour.

USED DATA

Precipitation

Rainfall data for the investigation were provided by the Sicilian Agro-meteorological Service (SIAS) and consist of the series of precipitation recorded at the rainfall gauging station of Catania S. F. La Rena, located on the east coast of Sicily close to Catania International Airport at an elevation of about 3 m above sea level.

The selected gauge has operated remotely since the year 2002. The average annual precipitation is 682 mm, with concentration of rainfall during the period September to February (see Figure 2).

Very recently, the gauging station has been updated to provide rainfall measurements with time resolution of 1 minute and accuracy of 0.2 mm. A complete 1-year data

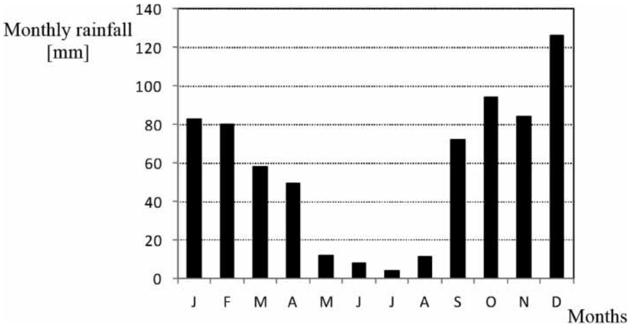

Figure 2 | Monthly distribution of observed rainfall at the considered rain station.

set (from 18 April 2013 to 17 April 2014) of precipitation records has been made available by SIAS and was here taken into account for the simulations. During the period the total observed precipitation was 481.6 mm, showing the year to be relatively dry if compared to the average annual value.

Rainfall depths at a time step of 1 minute for the whole year (and the respective inflow volumes Q_t to the tank) resulted in a series of 525,600 records.

Water demand

Data concerning water demand were extracted by the database using the results of a monitoring campaign conducted by the authors during the year 2006 in six Sicilian households. During that field campaign, the toilet water use pattern of the six households was monitored for a 2-week period each. The acquisition of data concerning the toilet use was carried out using specific electric sensors equipped with a data logger able to record the time instant of the toilet flush with an accuracy of 1 seconds for the whole monitoring period. For simplicity, the toilet cistern was assumed to be refilled instantaneously after the flush.

Table 1 | Main results of the monitoring campaign for the six households

Household	Total flushes during the 2 weeks	Average daily flushes (flushes/day/capita)
1	226	3.8
2	143	4.2
3	311	6.3
4	186	5.2
5	345	4.9
6	129	3.8

A description of the households' characteristics is detailed in Campisano & Modica (2010) together with the procedures followed to monitor consumption at each of the six households. The main results of the toilet demand monitoring campaign for the six households are summarized in Table 1.

To increase the size of the sample (and increase the statistical significance of final results) the data regarding the toilet demand for all the six households were grouped together, resulting in a virtual 'average' household. The described procedure was applied to such an 'average' household to generate the water demand series of the toilet at the 1-minute time scale.

The normal CDF used to fit the observed data of the 'average' household at the daily scale is plotted in Figure 3(a), together with the cumulated frequency of the observed per capita daily flushes (14 daily data for the 2-week period for each of the six households) that shows mean 4.69 flushes/day/capita and standard deviation 1.48 flushes/day/capita. An analysis of residuals to test the fitness of the CDF function to the measured data indicated a value of the root mean square error (RMSE) equal to 0.33 flushes/capita/day and a normalized RMSE equal to 0.0698. According to the test results, the CDF was then used to generate the synthetic series of the number of daily toilet flushes

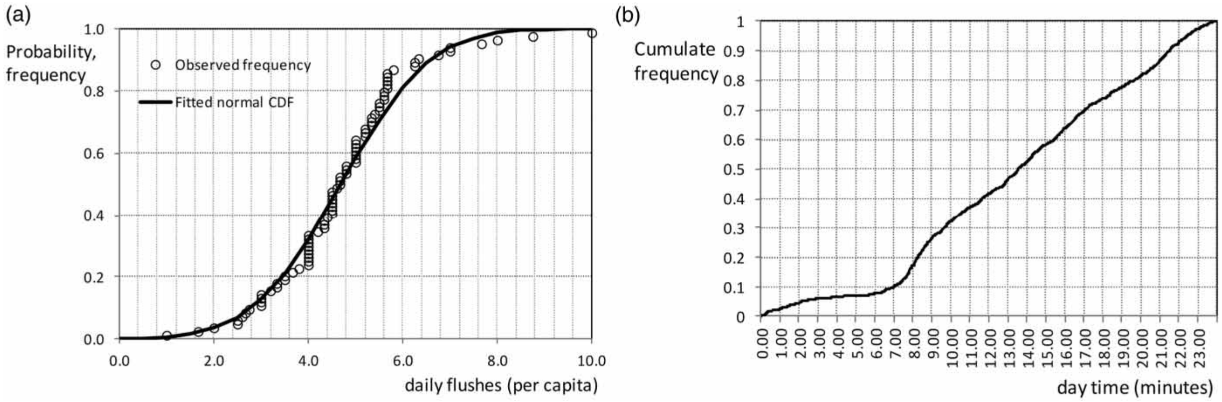

Figure 3 | (a) Fitted normal CDF to observed daily flush frequency; (b) cumulated relative frequency distribution of toilet use during the day.

for the whole year (by randomly picking 365 times from the CDF).

Then, recorded data were aggregated to determine the detailed intra-daily pattern of the frequency of use of the toilet for the 'average' household. The resulting cumulative frequency distribution for the 1-minute time step is plotted in the graph of Figure 3(b) and shows how flushes are distributed (on average for the 2 weeks of records) during the 24 hours for the considered 'average' household.

The obtained intra-daily pattern of toilet use is found to be very similar to patterns reported in other studies from the literature (Garcia *et al.* 2004; Blokker *et al.* 2010), with toilet use being mainly concentrated during early morning after the occupants awake (hours 7:00–8:00), and at night before going to sleep (hours 20:00–22:00).

According to the procedure, the distribution in Figure 3(b) was used to determine the series of the times (the minute) of occurrence of each toilet flush during the day for the whole year of simulation.

RESULTS OF THE SIMULATIONS AND DISCUSSION

Analysis of the overflow component from the water balance simulation of the tank allowed the investigation of the tank behavior with regard to its stormwater retention performance at the peak condition.

To show the behavior of the tank during rain events at the selected time scale, in Figure 4(a) the results of the tank simulation during the event of 22 February 2014 (total rainfall 4.8 mm, duration 11 minutes) are reported for $d = 1$ and $s = 0.5$. The event shows peak intensity of 1.2 mm/min (72 mm/h) at hour 14:16. At the beginning of the event, the tank was empty. The figure clearly shows that the rainwater tank basically provides an initial abstraction of volume from the rainfall event up to the achievement (at hour 14:15) of the condition of tank full (the tank retention capacity is reached). At that time, in fact, overflows from the tank start to occur. No rainfall reduction could be observed at peak time.

Results of the simulation of the same event for $d = 1$ and $s = 1$ (tank size is doubled compared to the previous case) are reported in Figure 4(b). Overflows from the tank in this case are delayed to hour 14:16 due to the increased retention capacity of the tank and, as a consequence, to a different succession of tank filling–emptying processes. More interestingly, the figure shows that the tank also has a positive effect on the reduction of the resulting runoff peak from 1.2 mm/min to about 1.05 mm/min (i.e., $E_{PR} = 12.5\%$).

Continuous simulation of the tank water balance for the entire year was carried out. As already found by Gerolin *et al.* (2010), the effect of peak roof runoff reduction was observed to occur for a number of rainfall events (over a total of 71 independent events), depending on the characteristics of each event (i.e., the position of the peak within the event) and of the tank (size, pre-event filling condition). A frequency analysis was conducted to evaluate the frequency of exceedance of the events characterized by specific E_{PR} values.

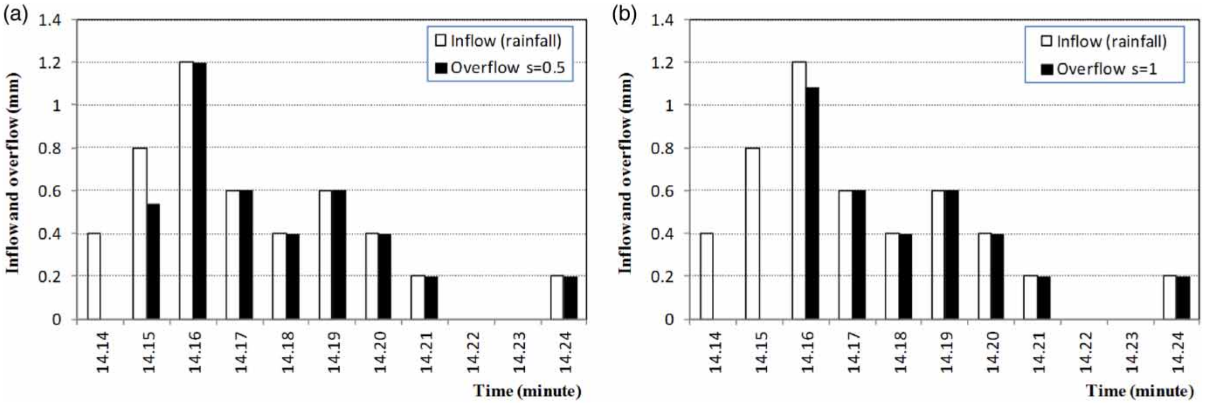

Figure 4 | Water balance simulation of the event of 22 February 2014: (a) simulation for $d = 1$ and $s = 0.5$; (b) simulation for $d = 1$ and $s = 1$.

Some of the results of all the simulations are presented in the dimensionless graphs of Figure 5. The figure reports the curves of the tank peak retention efficiency E_{PR} as a function of the cumulated relative frequency (of exceedance) of rainfall events in the year. The plotted curves are exemplificative of the condition for which the household is made by one user only (to discuss per capita results) and are relative to the different selected values of s. The graphs show results for $d = 0.5$, $d = 1.0$, $d = 2.0$, and $d = 4.0$, respectively.

The curves show abrupt drop (almost vertical) at the two boundary values of E_{PR} (close to 0 and close to 1), respectively. As expected, this behavior confirms that there is a relatively large number of events for which no peak reduction may be obtained, but also a significant number of events with runoff peak being totally abated.

Differently, for the other values of E_{PR}, the curves decrease monotonically showing smaller derivatives and pointing out a relatively limited number of events (for any condition in the order of 10–20% of the total events) having peak reduction efficiency between 0 and 1.

It is worth noting that curves show steps for specific values of E_{PR} (more evidently for $E_{PR} = 0.5$ and for larger values of d). This result was observed to depend on the precision of the used rainfall data (which are available as multiple values of 0.2 mm) and on the chosen simulation time step. In fact, as the tank achieves its maximum capacity S, it starts to produce overflows which are also multiple

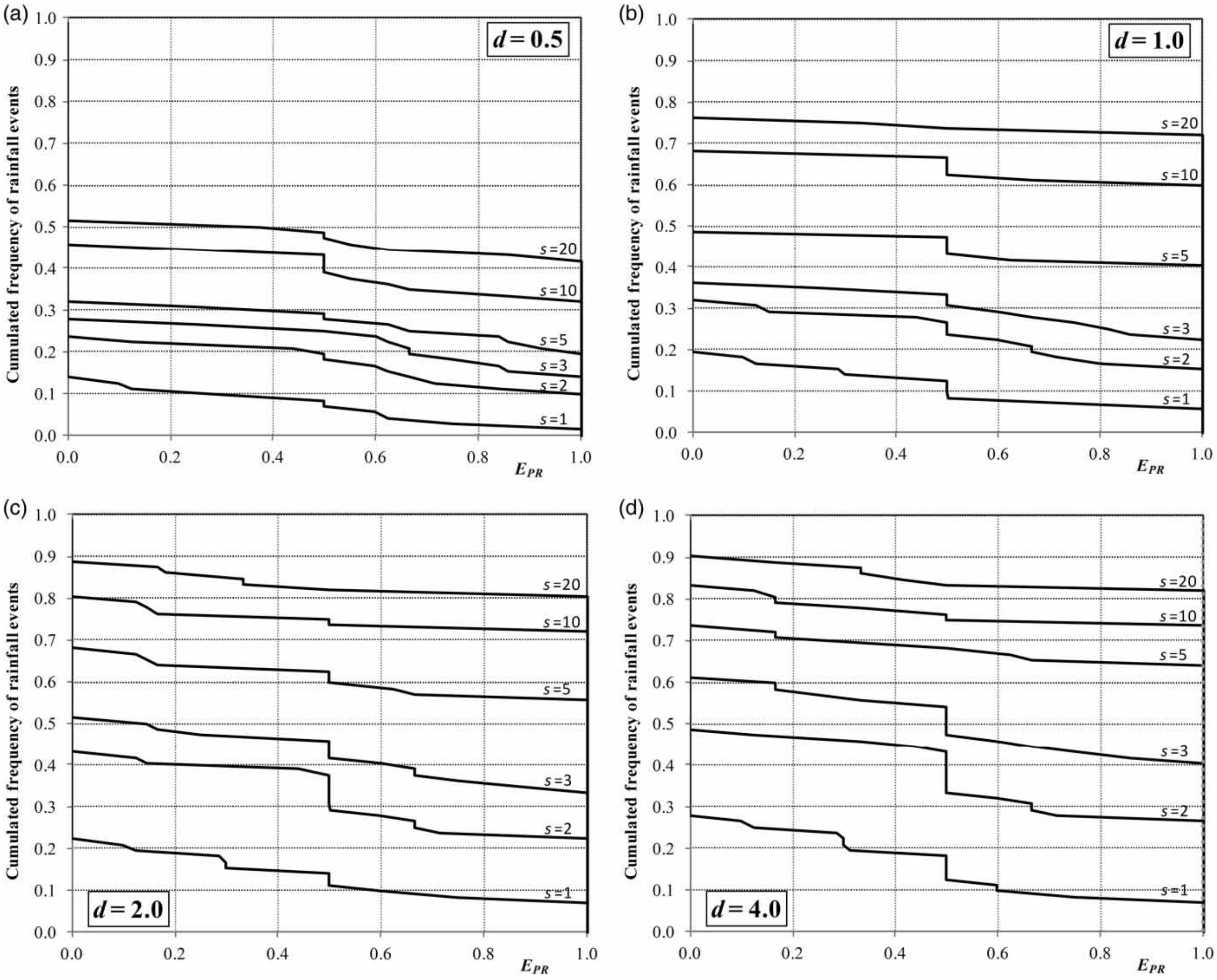

Figure 5 | Tank peak retention efficiency as a function of the cumulated relative frequency of rainfall events in the year. The household is assumed to host one person. (a) $d = 0.5$; (b) $d = 1.0$; (c) $d = 2.0$; (d) $d = 4.0$.

values of 0.2 mm, so that the values of E_{PR} constitute a series of discrete numbers in which the more frequent value is 0.5.

Looking globally to the graphs, the events for which the tank does not provide any reduction of the peak ($E_{PR} = 0$) strictly depend on s and d values. As expected, increased E_{PR} values are obtained for increasing values of s. For instance, Figure 5(b) (for $d = 1.0$) shows 80%, 52%, and 24% of the events having no peak reduction at all for $s = 1$, $s = 5$, and $s = 20$, respectively. However, the same graph shows also at least 5%, 40%, and 72% of the events having $E_{PR} = 1$, for $s = 1$, $s = 5$, and $s = 20$, respectively.

Moreover, the more the demand d for toilet is, the higher is the reduction of the runoff peak due to the augmented storage availability within the tank. For example, for a typical tank size value $s = 5$, the curves of the four presented diagrams show peak reductions in the range 30–68% for at least 50% of the events depending on the value considered for d.

The two graphs of Figure 6 show the analogous results (for $d = 1.0$ and $d = 2.0$) when water balance simulations are run assuming input series of toilet flushing demand being generated by considering the presence of four people in the house. As expected, due to the non-dimensional approach used, the effect of increasing the number of users in the house is almost negligible with curves almost overlapping those of Figure 5, except for curves generated for the small tank size ($s = 1$).

A specific analysis was carried out to analyze the number and average magnitude of the events that are characterized by $E_{PR} = 0$ and $E_{PR} = 1$. Table 2 summarizes results of this analysis for the demand scenario $d = 1$, as an example. The number of events N for which $E_{PR} = 0$ is observed to decrease monotonically from 57 (80% from 71 in total) to 22 (31%) as the storage fraction s increases from 1 to 10 (i.e., as the tank size increases). For the same reason, the number of events with $E_{PR} = 1$ increases from 5 (7%) to 44 (62%). These results are consistent with those obtained by Gerolin *et al.* (2010) for a rainfall series with characteristics very different from those used in this paper. In particular, according to the authors, the top 30 events of the rainfall series of Greenwich, UK showed the tank (estimated $s = 26$ and $d = 1.3$) to provide $E_{PR} = 0$ and $E_{PR} = 1$ for 44% and 6% of the events, respectively.

Table 2 also reports results in terms of average magnitude of the runoff peak of the event basically showing that events for which the full reduction of the runoff peak is obtained ($E_{PR} = 1$) are characterized by average peak of 14.4 mm/h to 22.9 mm/h as the storage fraction increases from $s = 1$ to $s = 10$. At the same time, events without any peak reduction ($E_{PR} = 0$) are characterized by average peak of 23.1–30.5 mm/h.

Importantly, the table indicates, as expected, that the events associated with $E_{PR} = 1$ are typically characterized by minor peak runoff values rather than those associated

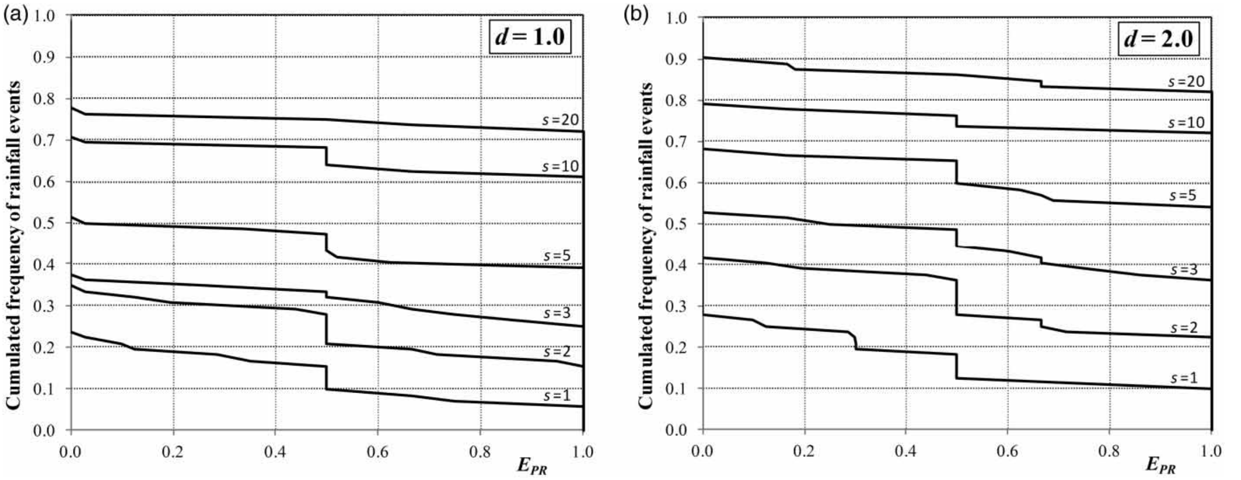

Figure 6 | Tank peak retention efficiency as a function of the cumulated relative frequency of rainfall events in the year. The household is assumed to host four people. (a) $d = 1.0$; (b) $d = 2.0$.

Table 2 | Number and average magnitude of the events for $E_{PR} = 0$ and $E_{PR} = 1$

	$s = 1$		$s = 3$		$s = 10$	
	N (-)	h_{av} (mm/h)	N (-)	h_{av} (mm/h)	N (-)	h_{av} (mm/h)
$E_{PR} = 0$	57	23.1	45	23.3	22	30.5
$E_{PR} = 1$	5	14.4	16	18.7	44	22.9

with $E_{PR} = 0$. In other words, only minor rainfall events are characterized by the full runoff peak abatement.

Results of the simulations were obtained by assuming the instantaneous refill of the toilet cistern with rainwater after the flush has occurred. This modeling hypothesis provides some tank outflows attributed to certain time steps to be partially shifted to the successive time step of the simulation. However, the resulting error can be neglected considering that the used time step of 1 minute is short enough when compared to the duration length of the measured rainfall events.

A limitation of the study is that the results discussed are obtained for a relatively dry 1-year period. According to Campisano & Modica (2015), this would result in an improved performance of the rainwater tank in terms of retained rain volumes. To assume the analogous tank performance in terms of runoff peak reduction is questionable and would require the analysis of the results of a long-term simulation over an appropriate number of years.

The used approach allowed estimation of the benefit of using rainwater tanks for peak roof runoff reduction in the case of free standing buildings. The results of the analysis may constitute support for successive investigations aiming at the evaluation of the potential for diffuse retention capacity at block and/or catchment scales. In these cases, the results of the analysis would need strict integration with appropriate urban drainage modeling approaches.

CONCLUSIONS

In this paper, the retention potential for roof runoff peak reduction of tank-based rainwater harvesting systems was explored for single household systems.

According to the aim of the analysis, water balance simulations were carried out using appropriate high temporal resolution sets of data of rainfall and household water demand at the toilet (1-minute time step), as input for the water balance model.

Data concerning toilet water consumption were extracted from the database of results of an experimental campaign involving six households in southern Italy. The procedure proposed by Campisano & Modica (2015) for the analysis of volumetric retention potential of RWH tanks was customized to disaggregate available daily demand data to the 1-minute time scale for the specific analysis of the peak runoff reduction.

The simulations were run using a dimensionless approach and showed the used time step to be appropriate for peak runoff analysis. Specifically, results showed that significant reduction of the peak may be obtained basically depending on the tank size and on the household water demand patterns. In particular, for a typical tank size characterized by storage fraction $s = 5$, results showed peak reductions in the range 30–68% for at least 50% of the events depending on the demand fraction value.

The tanks were demonstrated to have the potential to fully capture the peak for a significant number of rainfall events in the year (for the examined year). However, such rainfall corresponds to the events of the year characterized by relatively small peaks of intensity (from about 15–23 mm/h depending on the tank size and for demand fraction $d = 1$).

Results have been obtained for a relatively dry 1-year period. The generalization of the results would require the simulation of the system for a period of many years.

Together with traditional water saving purposes, results of the investigation open the discussion on using tank-based RWH as source control method to increase distributed retention in urban catchments and reduce runoff peak to the downstream drainage system. In this context, results may constitute support for successive investigations aiming at the evaluation of the potential for diffuse retention capacity at block and/or catchment scales.

REFERENCES

Blokker, E. J. M., Vreeburg, J. H. G. & van Dijk, J. C. 2010 Simulating residential water demand with a stochastic end-use model. *J. Water Resour. Plann. Manage.* **136** (1), 19–26.

Brodie, I. 2012 Stormwater harvesting and WSUD frequent flow management: a compatibility analysis. *Water Sci. Technol.* **66** (3), 612–619.

Burns, M. J., Fletcher, T. D., Duncan, H. P., Hatt, B. E., Ladson, A. R. & Walsh, C. J. 2014 The performance of rainwater tanks for stormwater retention and water supply at the household scale: an empirical study. *Hydrol. Process.* **29** (1), 152–160.

Campisano, A. & Modica, C. 2010 Experimental investigation on water saving by the reuse of washbasin grey water for toilet flushing. *Urban Water J.* **7** (1), 17–24.

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. 2015 Appropriate resolution time scale to evaluate water saving and retention potential of rainwater harvesting for toilet flushing in single houses. *J. Hydroinform.* **17** (3), 331–346.

Campisano, A., Di Liberto, D., Modica, C. & Reitano, S. 2014 Potential for peak flow reduction by rainwater harvesting tanks. *16th Conference on Water Distribution System Analysis, WDSA 2014*. Procedia Engineering, Bari, Italy.

Chilton, J. C., Maidment, G. G., Marriott, D., Francis, A. & Tobias, G. 1999 Case study of a rainwater recovery system in a commercial building with a large roof. *Urban Water* **1** (4), 345–354.

Cook, S., Sharma, A. & Chong, M. 2013 Performance analysis of a communal residential rainwater system for potable supply: a case study in Brisbane, Australia. *Water Resour. Manage.* **27** (14), 4865–4876.

Fewkes, A. & Butler, D. 2000 Simulating the performance of rainwater collection systems using behavioural models. *Build. Serv. Eng. Res. Technol.* **21** (2), 99–106.

Garcia, V. D., Garcia-Bartual, R., Cabrera, E., Arregui, F. & Garcia-Serra, J. 2004 Stochastic model to evaluate residential water demands. *J. Water Resour. Plann. Manage.* **130** (5), 386–394.

Gerolin, A., Kellagher, R. B. & Faram, M. G. 2010 Rainwater harvesting systems for stormwater management: Feasibility and sizing considerations for the UK. In: *Proceedings of NOVATECH 2010, Lyon, France, 27 June–1 July 2010.*

Ghisi, E. & Ferreira, D. F. 2007 Potential for potable water savings by using rainwater and greywater in a multi-story residential building in southern Brazil. *Build. Environ.* **42** (4), 2512–2522.

Glist, D. 2005 Rainwater down the toilet. *Pollut. Eng.* **37** (4), 40–41.

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.

Kus, B., Kandasamy, J., Vigneswaran, S. & Shon, H. K. 2011 Water quality in rainwater tanks in rural and metropolitan areas of New South Wales, Australia. *J. Water Sustain.* **1** (1), 33–43.

Mitchell, V. G., Deletic, A., Fletcher, T. D., Hatt, B. E. & McCarthy, D. T. 2007 Achieving multiple benefits from stormwater harvesting. *Water Sci. Technol.* **55** (4), 135–144.

Mitchell, V. G., McCarthy, D. T., Deletic, A. & Fletcher, T. D. 2008 Urban stormwater harvesting – sensitivity of a storage behaviour model. *Environ. Modell. Softw.* **23**, 782–793.

Petrucci, G., Deroubaix, J. F., de Gouvello, B., Deitsch, J. C., Bompard, P. & Tassin, B. 2012 Rainwater harvesting to control stormwater runoff in suburban areas. An experimental case-study. *Urban Water J.* **9** (1), 45–55.

Ward, S., Memon, F. A. & Butler, D. 2012 Performance of a large building rainwater harvesting system. *Water Res.* **46**, 5127–5134.

Zaizen, M., Urakawa, T., Matsumoto, Y. & Takai, H. 1999 The collection of rainwater from dome stadiums in Japan. *Urban Water* **1**, 355–359.

Zhang, X., Hu, M., Chen, G. & Xu, Y. 2012 Urban rainwater utilization and its role in mitigating urban water logging problems: a case study in Nanjing, China. *Water Resour. Manage.* **26**, 3757–3766.

First received 24 November 2014; accepted in revised form 13 May 2015. Available online 24 June 2015