Appropriate resolution timescale to evaluate water saving and retention potential of rainwater harvesting for toilet flushing in single houses

Alberto Campisano and Carlo Modica

ABSTRACT

The main objective of the paper is to identify the appropriate temporal scale for modeling the behavior of rainwater harvesting tanks in relation to the purpose they are built for, i.e., water saving, stormwater retention potential, etc. A tank water balance model coupled with a specific procedure to determine long-term series of rainfall (tank inflow) and toilet flushes (tank outflow) at different daily and sub-daily resolution timescales was developed. The model was applied to a household case study for which detailed water demand data are available from measurements. Simulations show that the daily scale may be reliably chosen to evaluate the tank water saving efficiency. In contrast, sub-daily resolutions (at least the hourly time step) are needed for the evaluation of the tank retention efficiency to limit inaccuracies, especially for small tanks and for high values of the water demand. Moreover, preliminary results at the 5 min time step show that rainwater tanks can help in reducing the rainfall intensity peak, basically depending on the tank storage and on the rainfall event characteristics.

Key words | behavioral models, rainwater tanks, resolution timescale, storm water retention, water saving

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INTRODUCTION

Today, the old practice to harvest rainwater for domestic use is reviving in many countries due to its potential to address a number of environmental and social issues. Rainwater harvesting (RWH) defines the small-scale concentration, collection, storage and local use of rainwater coming from rooftops, courtyards and other impervious building surfaces. In cities experiencing water scarcity, tank-based RWH is considered as a complementary water supply method that can help in saving potable water from the mains (Cook *et al.* 2013). The volume of potable supply substitution is the primary reason that motivates municipalities to support RWH installation also with the function of back-up supply source (Mitchell *et al.* 2008).

Rainwater normally shows low hardness, a quasi-neutral pH, and is often free of sodium (Farreny *et al.* 2011; Van der Sterren *et al.* 2013; Morales-Pinzón *et al.* 2014). For these positive characteristics, collected rainwater is worldwide utilized for both indoor and outdoor non-potable consumption (i.e., toilet flushing, washing machine use, garden irrigation, terrace cleaning, car washing, etc.). In particular, several studies have recognized that, with basic treatment (filtration and/or chlorination), the use of harvested rainwater for toilet flushing may provide high drinking water saving potential (Lazarova *et al.* 2003; Glist 2005; Kus *et al.* 2011).

Different from urban contexts, in rural areas rainwater tanks may be the only way to supply water to detached households, as such areas may not be served by water supply network infrastructures (Sturm *et al.* 2009). Besides, in specific geographical contexts these waters have been identified as a major source also for drinking, cooking and sanitary purposes (Dunker 2001) since they did not present increased risk of gastrointestinal illness when compared with water from public mains (Heyworth 2001; Abdulla &

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Al-Shareef 2009). Under these conditions, RWH systems have to be designed to have high water quantity and quality reliability in order to meet the desired household demand.

Rainwater tanks are also recognized as one of the best management practices to mitigate environmental impacts of urbanization on storm water drainage systems and receiving water bodies (Petrucci *et al.* 2012; Zhang *et al.* 2012; Campisano & Modica 2014). The increase of the retention capacity throughout urban catchments can help in reducing the frequency and volume of storm water runoff conveyed by downstream drainage systems and may contribute to partially restore the altered water balance of the catchment (Burns *et al.* 2014).

From this viewpoint, RWH operates as a storage-based source control solution: during storm events, part of the rainfall is captured and stored in the rainwater tanks with the effect of reducing the runoff component. However, different from traditional storm water storages, the water abstraction obtained by rainwater tanks is demand-driven (Petrucci *et al.* 2012), with demand magnitude and patterns having an effect on the design and efficiency of the tank (Mitchell *et al.* 2008).

Household-scale experimental studies on the performance of rainwater tanks have been conducted in various countries, basically using the collected rainwater for toilet flushing (Chilton *et al.* 1999; Zaizen *et al.* 1999; Ward *et al.* 2012). These studies indicate that the RWH system water saving 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 in the household, etc.

Besides, further investigations based on data acquired during monitoring of implemented systems allowed the assessment of storm water retention benefits of RWH. In particular, the results concerning the impact of a number of small rainwater tanks in a suburban catchment of Paris, France, show that RWH alone is not able to prevent overflows from the storm water drainage system (Petrucci *et al.* 2012). However, studies on the performance of 12 rainwater tanks in Australia have shown that, under regular and sufficiently large demands, RWH may achieve storm water retention performance approaching that of the same area under the pre-development condition (Burns *et al.* 2014).

Multiple benefits of RWH tanks have also been explored using behavioral models based on the long-term water balance simulation of the tank, with rainfall and household water demand being the typical tank inflow and outflow, respectively (Ghisi & Ferreira 2007; Mitchell *et al.* 2007; Brodie 2012; Campisano & Modica 2012; Agudelo-Vera *et al.* 2013; Campisano *et al.* 2013; Leusbrock *et al.* 2013). Such studies reveal that simulation results may be affected by the model structure and parameters. In particular, the resolution timescale that is chosen for the analysis (and then the time step selected for computations) may influence the estimation of the tank design/reliability in a significant way (Mitchell *et al.* 2008).

In this context, early results by Fewkes & Butler (2000) indicate that simulations with monthly time steps may provide inaccurate evaluation of the water saving performance of RWH systems and suggest using the daily time step resolution for water balance calculations. However, the daily resolution may be still insufficient if the aim of the analysis is to evaluate the tank potential to reduce runoff. For this purpose, a more accurate estimation would probably require increased time resolutions under a wide spectrum of conditions. High time resolutions become mandatory if the tank effect on storm water peak reduction is analyzed (Campisano & Modica 2014).

The choice of the time resolution for modeling the tank operation strictly depends on the availability of rainfall and water demand data and has obvious repercussions on both the accuracy of the results and on the required computational efforts to treat extended data sets. Then, a specific analysis is needed to define the appropriate modeling time resolution, depending on the purpose driving the implementation of the RWH system and on the expected accuracy of the results.

In this paper, an extension of methods and results shown in Campisano & Modica (2014) is presented together with an example of the application of the procedure for the evaluation of the potential of RWH techniques.

The overall objective of the present paper is to provide a contribution to the modeling of tank-based RWH systems at different resolution timescales. The following specific objectives are focused on:

- exploring the tank potential for both water saving and retention purposes;
- identifying appropriate time resolutions for modeling the tank behavior in relation to the desired purpose (water saving benefit and retention potential);

- providing a preliminary evaluation of the tank potential to reduce the rainfall intensity peak.

To achieve these objectives, the analysis was carried out with reference to a pilot test household localized in a village in southern Italy. Available data for this household concern toilet use frequency during a 2-week-long campaign aimed at monitoring the household water consumption (Campisano & Modica 2010).

A specific procedure to derive yearly series of household water demands at different resolution timescales from observed patterns was developed. Derived water demand series were used together with high temporal resolution rainfall series to run the water balance simulation of the tank at different daily and sub-daily time steps and to explore the tank potential for RWH.

METHODOLOGY

The analysis was carried out using a simulation framework which consists of three major components/modules basically focusing on: (i) the evaluation of the rainwater inflow to the tank; (ii) the estimation of the toilet flushing demand pattern; and (iii) the simulation of the tank water balance. Each model component is part of a proprietary software tool which was specifically developed at the University of Catania for the study of RWH systems and is described in detail as follows.

Inflow to the tank

The rainwater tank is considered to be filled exclusively by rainfall volume precipitated on the building rooftop, in this way excluding any link with mains and/or connections conveying water from other sources present in the house.

Assuming the rainfall to be constant within each computational time step t, the volume of rainwater adducted to the tank is calculated as

$$Q_t = \phi \cdot R_t \cdot A_{\mathrm{TOT}} = R_t \cdot A \quad (1)$$

where Q_t [m^3] is the inflow volume supplied to the tank at time step t; ϕ [–] is the runoff coefficient depending on water losses; A_{TOT} [m^2] is the total rooftop area for rainwater collection connected to the tank; $A = \phi \cdot A_{\mathrm{TOT}}$ [m^2] is the effective impervious area of the rooftop; and R_t [m] is the rainfall at time step t.

Equation (1) requires the availability of precipitation data to evaluate the long-term series of Q_t volumes entering the tank at each time step of the water balance simulation. Then, high-resolution records of precipitation events over a determined period have to be provided as input to the rainwater inflow module.

Disaggregated data are normally provided by regional/national water agencies from rain gauges belonging to telemetry networks and typically consist of the series of bucket tipping event signals and the corresponding times of occurrence.

In the module, to assure high reliability of the rainfall series, disaggregated data are first filtered to eliminate outliers (due to acquisition errors). Then, filtered records are aggregated at desired temporal intervals to obtain yearly precipitation series at different scales of time resolution. Basically, daily, hourly and sub-hourly aggregation timescales can be selected and they allow to take into account the intra-annual pattern of precipitation in the analysis of rainwater tank performance.

Household demand pattern

A module based on a two-phase procedure is developed to determine the household toilet demand pattern at different time resolutions.

The first phase is aimed at determining toilet daily demands over the year, i.e., the number of daily toilet flushes occurring in the house during each of the 365 days of the year. To achieve such an aim, the procedure needs data on the users' habits concerning both the daily frequency of toilet use and the number of users present at home during the day. These data may be obtained through continuous monitoring of the household. Otherwise, data from literature cases related to households with similar characteristics can be assumed. In any case, the monitoring period should be long enough to identify at least the weekly pattern of toilet flushing use and of the user presence at home. The procedure can be schematized according to the following steps:

(1) Obtaining daily data from the monitoring period by summing flushes occurring between hour 00:00 and hour 24:00 of each day.

(2) Using information concerning the daily presence of users at home to compute per capita toilet flushes for any day of the monitoring period.
(3) Selecting a probability distribution function (PDF) that shows to fit well with the cumulative frequency of the obtained per capita flushes. In particular, following Garcia *et al.* (2004), Poisson and normal PDFs can be considered in the procedure for such a purpose.
(4) Assuming the chosen PDF to represent the toilet use daily pattern for the whole year. Accordingly, 365 random picks (with uniform distribution) have to be sampled from the PDF to generate the daily (per capita) toilet flushes for all the days of the year.
(5) Computing the series of daily toilet flushes (for the household) by simply multiplying flushes resulting from Step 4 for the number of users at home during the day. Toward this aim, the average number of users per day is considered in absence of specific information concerning the presence of users at home during the days of the year.

The second phase of the procedure allows for scaling the toilet use daily pattern down to hourly and sub-hourly temporal resolutions. The procedure is based on defining appropriate intra-daily patterns of toilet use frequency, starting from the observed daily pattern. Basically, the procedure consists of the following steps:

(1) Each day of the period of observation is analyzed separately, focusing on each monitored flush event and labeling its time of occurrence (day, hour, minute) during the day.
(2) Flushes during the day are aggregated using different sub-hourly and hourly chronological intervals; for example, if the hourly aggregation scale is chosen, 24 time intervals per day are allocated (from 0:00:00 a.m. to 0:59:59 a.m., from 1:00:00 a.m. to 1:59:59 a.m., etc.) and each observed flush is assigned to the proper time interval depending on the recorded daytime of occurrence. Step 2 is repeated for any day of the monitoring period.
(3) Obtained daily chronological series of aggregated flushes are 'overlapped' and flushes falling within the same time interval of different days are summed.
(4) Obtained flushes associated with intervals are cumulated and normalized to the total number of flushes observed during the whole monitoring period to obtain cumulative relative frequency distributions (CFDs) of toilet use during the day for each selected sub-daily scale of aggregation (intra-daily demand patterns).
(5) Random picks (with uniform distribution) from the obtained CFDs (in number equal to the household daily flushes resulting from phase one) allows determination of the sub-hourly/hourly daytime intervals to be assigned to each flush.
(6) The previous Step 5 is repeated for all the days of the year to obtain the series of toilet flushes to be used later as input for the tank water balance simulation at the various temporal resolutions.

Water balance simulation of the tank

A scheme that is typically used for the setup of domestic RWH systems for single houses or free standing buildings was considered in the present study.

The scheme provides the collection of rainwater precipitated onto the building roof. The rainwater is temporarily stored within the rainwater tank that is equipped with a dedicated piping system (disconnected by the mains) allowing a supply of rainwater to the toilet cistern(s). The toilet is assumed to use primarily the water accumulated in the rainwater tank, i.e., the water from the mains is sourced to the toilet only in the case that the tank is empty.

A specific module was implemented for behavioral analysis of the tank (Campisano & Modica 2012). The module uses a continuous simulation routine to track tank inflows and outflows, as well as the change in storage volume. The routine is based on the yield-after-spillage algorithm as tank release rule (Jenkins *et al.* 1978)

$$Q_{Dt} = \max\begin{cases} V_{t-1} + A \cdot R_t - S \\ 0 \end{cases} \tag{2}$$

$$Y_t = \min\begin{cases} D_t \\ V_{t-1} \end{cases} \tag{3}$$

$$V_t = \min\begin{cases} V_{t-1} + A \cdot R_t - Y_t \\ S - Y_t \end{cases} \tag{4}$$

where Q_{Dt} [m^3] is the volume discharged as overflow from the storage tank at time t, V_t [m^3] is the volume in store at time t, Y_t [m^3] is the yielded volume of rainwater from the storage tank at time t, D_t [m^3] is the toilet water demand at time t and S [m^3] is the tank storage capacity.

Evaluation of the performances of rainwater tanks has been conducted using numerous performance measures/indicators (McMahon *et al.* 2006). Two basic performance indicators widely adopted in the literature (Mitchell *et al.* 2008; Campisano & Modica 2014) were considered for use in this study: tank water saving efficiency E_{WS} [%] and tank volumetric retention efficiency E_R [%].

The water saving efficiency is a measure of the volumetric reliability of the tank and is defined as the ratio between the volume of rainwater supplied to the house (yield) and the total demand during the entire simulation period (the whole year in the present study), according to the following equation:

$$E_{WS} = \frac{\sum Y_t}{\sum D_t} \times 100 \tag{5}$$

where sums are extended to all the time steps of the year.

Water saving efficiency assumes value 0% if there is no yield from the rainwater tank (for example, if only water supplied from the mains is used) and it assumes value 100% if only the stored rainwater is used by the devices connected to the tank.

The volumetric retention efficiency is a measure of the capability of the tank to retain rainwater volumes, then reducing storm water runoff downstream (over the catchment surface or flowing into the storm water sewer system). The following equation is used to determine the tank volumetric retention efficiency:

$$E_R = \left[1 - \frac{\sum Q_{Dt}}{\sum A \cdot R_t}\right] \times 100 \tag{6}$$

where the second of the two terms in square brackets provides the ratio between the sum (over the year) of the tank overflow volumes and the sum of rainwater volumes flowing into the tank. Equation (6) clearly shows that E_R tends to 0% when the sum of discharged volumes Q_{Dt} tends to the sum of AR_t that may occur in those cases characterized by small tanks and/or reduced rainwater demands. Oppositely, if the tank is large and/or the household demand for rainwater is high, the tank may provide significant retention performances with E_R approaching value 100%.

In addition to E_{WS} and E_R, a novel performance indicator was introduced here, namely the peak retention efficiency E_{PR} [%], defined as

$$E_{PR} = \left[1 - \frac{Q_{Dpeak}}{A \cdot R_{peak}}\right] \times 100 \tag{7}$$

where Q_{Dpeak} [m^3] and R_{peak} [m] are the volume discharged as overflow from the storage tank and the rainfall at peak time intervals, respectively. E_{PR} is a measure of how much the storage tank is able to reduce/retain the peak of rainfall intensity of the precipitation event. Different from indicators (5) and (6), E_{PR} is evaluated for each event separately and its evaluation may provide significant information only if appropriate (high) temporal resolutions are considered for the tank water balance.

The performance of rainwater tanks as part of RWH systems is affected by several variables. Basically, the characteristics of the installation (i.e., rainwater tank storage capacity) and of the building (effective rooftop collection area) together with the household demand patterns and with the rainfall characteristics (average precipitation and dry weather inter-event period) appear crucial to evaluate the tank efficiency.

There is also the potential for reciprocal dependency between the involved variables that may create ambiguity when a sensitivity analysis of variables on the obtained results is performed. In this connection, Mitchell *et al.* (2008) observed that it could be a too onerous task to investigate such interdependencies because the number of modeling scenarios to potentially examine would be extremely high.

It was therefore decided to explore the tank performances by following a non-dimensional approach based on evaluating results of the simulations with the use of dimensionless parameters. In particular, to consider different combinations of tank storage capacity, roof area, toilet water demand and precipitation, two parameters that are well consolidated in the literature were taken into account for the simulations, namely the demand fraction d and the storage fraction s (Fewkes & Butler 2000)

$$d = \frac{D_d}{A \cdot R_d} \tag{8}$$

$$s = \frac{S}{A \cdot R_d} \tag{9}$$

with D_d and R_d being the average (in the year) daily values of toilet water demand and rainfall, respectively.

The use of the dimensionless parameters described by Equations (8) and (9) allows the grouping of variables that have an influence on the process and simplification of the sensitivity analysis of parameters on the results of the simulations. According to this approach, values of d and s have to be selected for the model application. The selection of demand and storage fractions is conducted based on the range of values that household demand, tank storage capacity, rooftop area, and precipitation may assume in the practice.

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. For the specific purposes of the research, the influence of such distribution is directly taken into account at the time that rainfall and water demand intra-daily patterns are used for the water balance simulation of the tank.

CASE STUDY

The case study of a single household was considered in the paper to test the described methodology. The selected household is located in Patti, a relatively small village close to the northern coast of Sicily, Italy. The household is described in Campisano & Modica (2010) and pertains to a private apartment hosting a family of five people (four employees and one housewife). One toilet is installed in the bathroom of the house.

In March 2006, the homeowner was contacted to ask for permission to monitor water consumption habits in the house with specific reference to the bathroom toilet and washbasin. After agreement, a 2-week-long monitoring campaign (from 1 May 2006 hour 7:30 p.m. to 15 May 2006 hour 7:30 p.m.) was launched to determine toilet and washbasin water use patterns (i.e., frequency of use, daily averages, etc.). Data concerning the toilet use (that are of interest for the present investigation) were acquired using an electric sensor connected to the toilet cistern push button and equipped with a data logger (Series HOBO U-11). The device allowed continuous recording of the times the toilet was flushed during the whole monitoring period with an accuracy of 1 second.

A total of 345 flushes were observed during the monitoring period with average 24.64 flushes/day. Results are in good agreement with findings of previous studies available from the literature (Buchberger & Wells 1996; Garcia *et al.* 2004) and showed the number of daily toilet flush events (per capita) monitored during the experiments to be almost constant during the week, without significant differences between weekdays and weekends. Also, no outliers were observed that may indicate the evidence of acquisition errors during the monitoring phase.

However, as was expected, the sub-daily distribution of flushes is far from being uniform with flushes being majorly concentrated during specific daylight hours. As an example, Figure 1 shows the hourly distribution of the 28 flushes that occurred during Thursday 11 May. In particular, as already shown in previous studies (Blokker *et al.* 2010), the toilet use in the house is observed to strongly depend on whether people are at home or not and if they are asleep, getting up or preparing for bed.

For application of the procedure, an audit of people living in the house was conducted to establish the effective number of users present at home during each day of the data acquisition period (five people). In the absence of specific information for the other days of the year, the same number of users was later considered for simulation of the whole year.

Rainfall data for the investigation were provided by the Sicilian Department of Water and Waste and consist of the high-resolution precipitation series recorded at the rainfall gauging station of Elicona a Falcone, located around 9 km east of the household site at about 14 m above mean sea level. The selected gauge has operated remotely since the year 2002. The average annual precipitation is

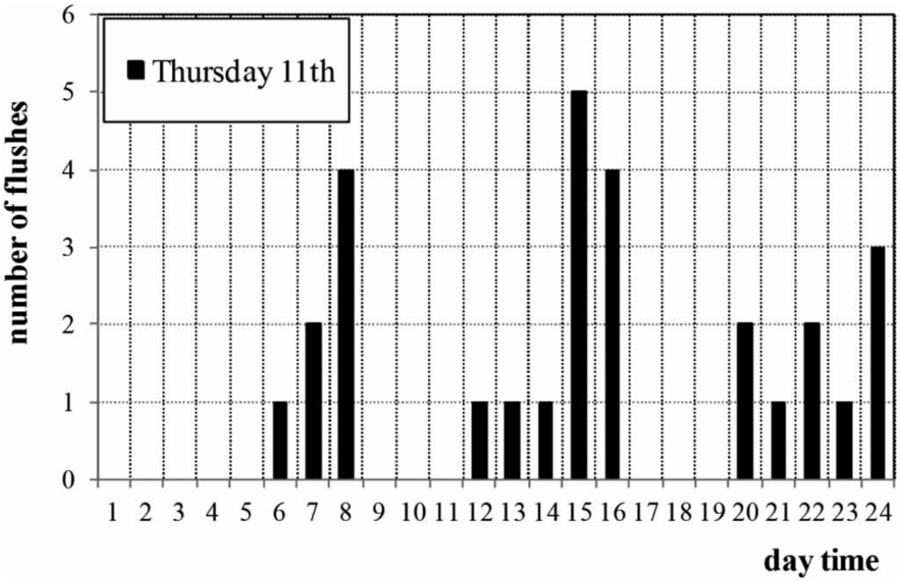

Figure 1 | Hourly distribution of toilet flushes during Thursday 11 May 2006.

approximately 577.0 mm and the average annual number of rainy days is about 82.

Precipitation for the year 2006 was taken into account correspondingly to the year of the monitoring campaign and because it has a complete series of records. For 2006 the total observed precipitation was 475.0 mm, with the major concentration of rainfall during the period January–March (see the monthly rainfall distribution in Figure 2).

MODEL SETUP AND SIMULATION FRAMEWORK

The developed model was applied to the pilot case study in order to test the developed methodology and to explore the tank potential for water saving and stormwater retention at different resolution timescales.

After preliminary analysis, four temporal resolutions were considered for simulations: the daily scale (data

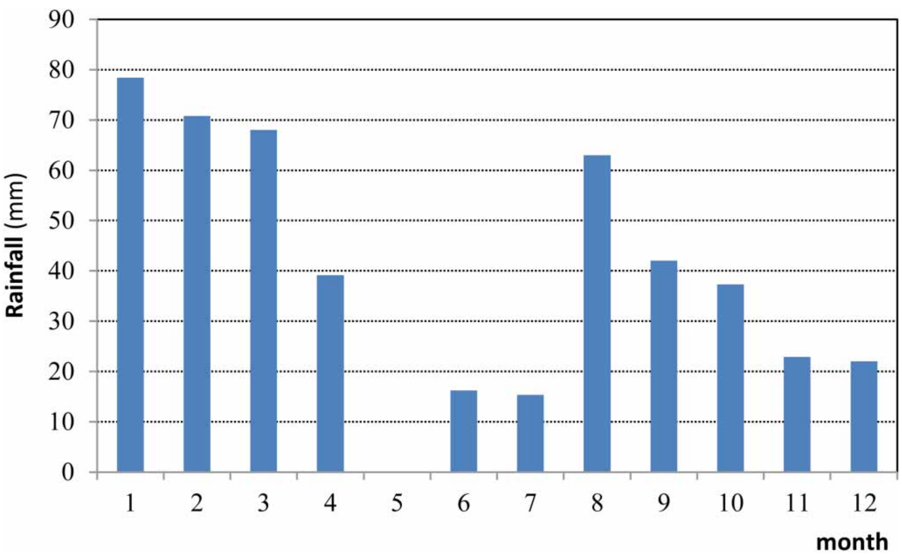

Figure 2 | Monthly rainfall distribution for Elicona a Falcone rain gauge (year 2006).

aggregated at 24 hour) and three sub-daily scales corresponding to time intervals of 1 hour, 15 min, and 5 min, respectively. The last two scales also allowed analysis of the tank behavior and the results of the simulations at sub-hourly level.

Inflow volumes to the tank

Raw data concerning recorded precipitation events during the year 2006 were preliminary filtered to eliminate outliers. Rainfall depths were then aggregated in order to obtain four annual rainfall series characterized by resolution timescales of 5 min, 15 min, 1 hour, and 24 hour (daily). In the end, resulting series consisted of 105,120, 35,040, 8,760 and 365 data, respectively. Equation (1) was finally used to determine the four respective series of inflow volumes Q_t for the water balance simulation of the tank at the selected scales of resolution.

Household demand patterns

The procedure described in the methodological chapter was applied to the data recorded during the experimental monitoring of the household case study. The normal PDF was used to fit the observed data. The PDF is plotted in Figure 3, together with the observed cumulated frequency *F* of per capita daily flushes (14 daily data for the 2-week period having mean 4.93 flushes/day/capita and standard deviation 0.57 flushes/day/capita). The figure evidently shows that the normal PDF fits properly to the recorded data. Thus, it was considered to represent well the household toilet use daily pattern and later used (by performing 365 random picks) to generate the synthetic series of the number of daily toilet flushes for the whole year.

Recorded data aggregated at the selected hourly (1 hour) and sub-hourly (15 and 5 min) timescales were used to determine sub-daily patterns of toilet frequency of use. A CFD of toilet use during the day was obtained for each of the three sub-daily resolutions, by following the procedure described earlier. As an example, the obtained CFD for the 5 min time step is plotted in the graph of Figure 4 and shows how the flushes are distributed (on average for the 2 weeks of records) during 24 hours in the examined household (intra-daily demand pattern). The household pattern of toilet use was found to be similar to patterns reported in other studies from the literature (Garcia *et al.* 2004; Blokker *et al.* 2010). The figure shows that use of the toilet is mainly concentrated in the early morning when people are waking up (from about 6 a.m. to 8 a.m.), afternoon (from about 2:30 p.m. to 5 p.m.), and night before going to sleep (from about 9 p.m. to midnight). As expected, the frequency of use is very small

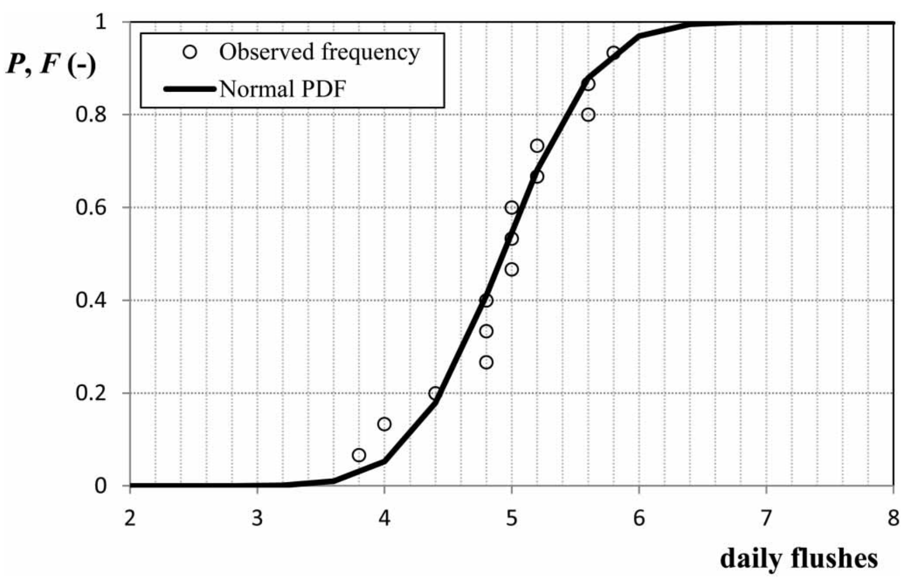

Figure 3 | Fit of normal probability function to the observed cumulated frequency *F* of (per capita) daily flushes for the monitoring period (household daily demand pattern).

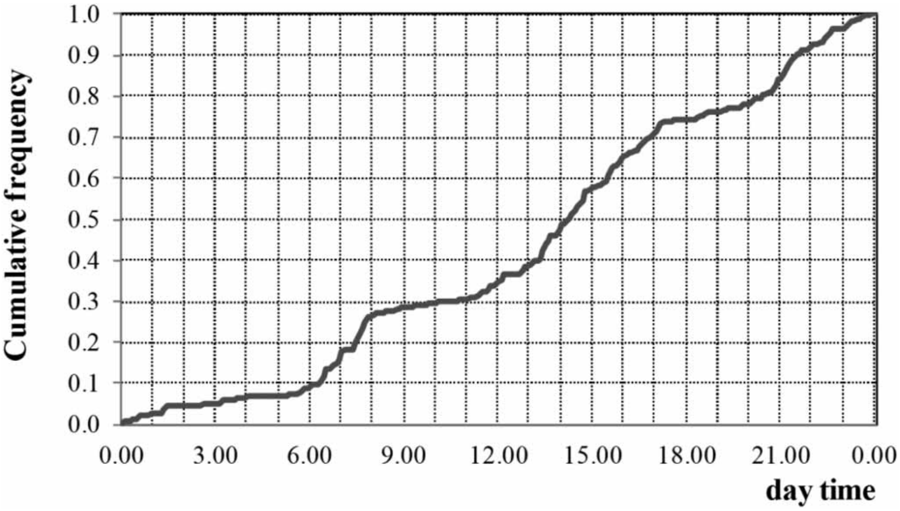

Figure 4 | Cumulative relative frequency distribution of the toilet use during the day at the 5 min resolution timescale (household intra-daily demand pattern).

during the night hours (between midnight and 5 a.m. less than 7% of the total flushes). Finally, according to the proposed procedure, the obtained CFDs were used to generate the synthetic series of flushes for all the days of the whole year.

Water balance simulation scenarios

Simulations were run with reference to various scenarios characterized by different range of values of tank size S, daily water demand D at the toilet (as obtained by product of cistern size times the average number of daily flushes per capita times the average number of people in the house), total roof area A_{TOT}, roof runoff coefficient ϕ and average daily rainfall R_d. In particular, tanks with size S between 0.1 and 20 m^3, 6–9 L toilet cisterns, daily toilet water demand D between 30 and 300 L/day, total roof area between 50 and 180 m^2, roof runoff coefficient ranging between 0.8 and 0.9, and average daily rainfall between 1 and 2.5 mm were considered to determine the values of the demand and storage fractions d and s to be adopted for the simulations. Basically, four values of d were assumed. In particular, the value $d = 0.5$ was chosen thus corresponding to limited demand fraction. The value $d = 1.0$ was selected to consider the demand to be balanced by the stored rainwater. The other two values ($d = 2.0$ and $d = 4.0$) were selected as representative of high demand conditions.

Seven values of storage fraction were used, with s equal to 1, 2, 3, 5, 10, 20 and 40. The minimum value of s adopted for the simulations ($s = 1$) was selected in order to comply with constraints suggested by Fewkes & Butler (2000) to avoid inaccuracies in simulation results at the daily timescale. Globally, the combination of the different values of d and s required to simulate 28 different cases for each of the four selected resolution timescales.

RESULTS AND DISCUSSION

Water saving efficiency

Part of the results of the simulations are presented in the dimensionless graphs of Figure 5. The figure reports the curves of the tank water saving efficiency versus the storage fraction s for the different resolution timescales adopted in the analysis. In particular, the four graphs show results for the different chosen values of demand fraction d, respectively.

Looking at the water saving performance of the system, the graphs globally indicate that E_{WS} values monotonically increase as the storage fraction s increases. In other words, increased water saving efficiencies are obtained for tanks with increasing storage capacity with respect to the average daily rainfall volume. Notably, for $d = 0.5$ the water saving efficiency quickly rises up to about 100%.

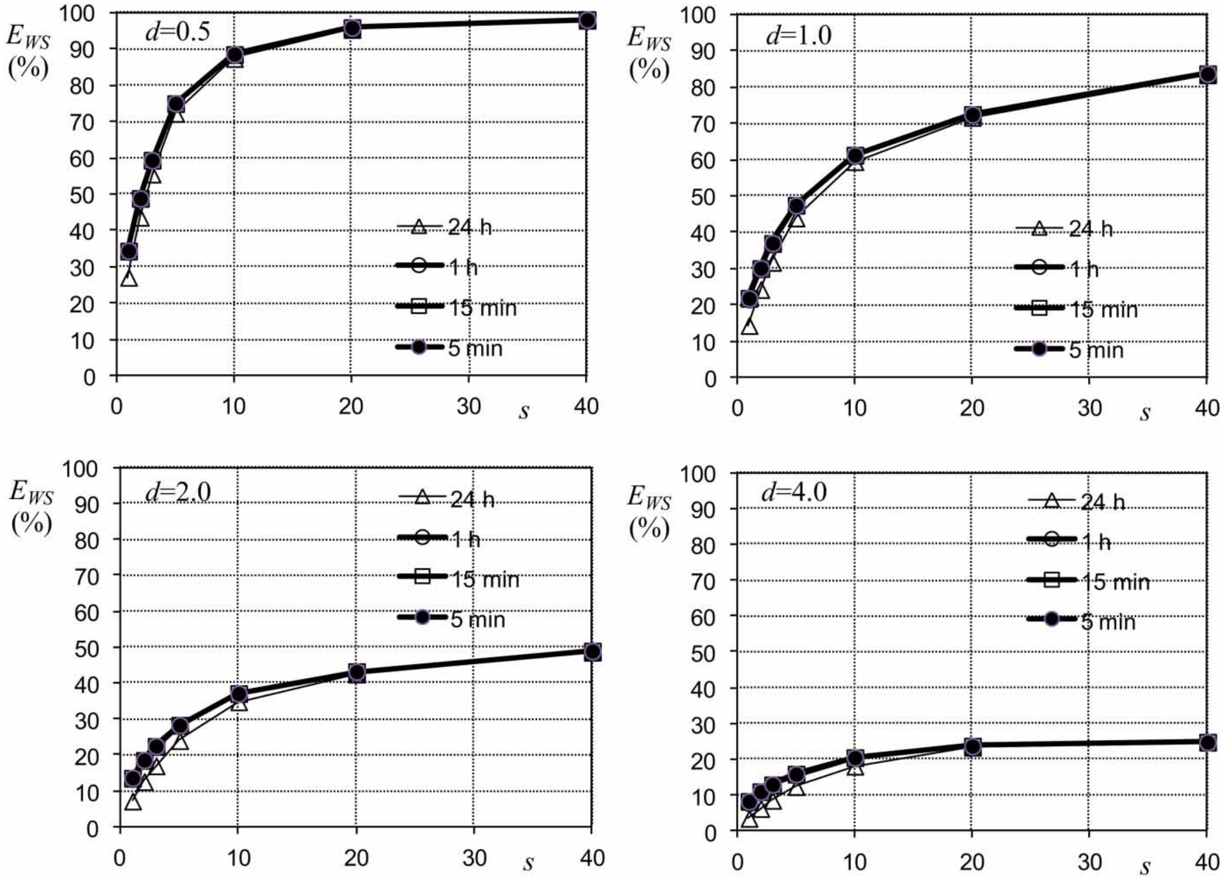

Figure 5 | Evaluation of tank water saving efficiency at the different selected resolution timescales.

That is, in the case of low demand at the toilet, a very high harvesting performance can be obtained also with tanks of relatively small size. Moreover, curves tend to flatten (derivatives tend to decrease) as *s* increases, revealing that reduced marginal water saving benefits can be obtained as the storage fraction increases.

Concerning the influence of the demand fraction, the comparison of the four graphs globally shows that curves of E_{WS} rise as *d* decreases, i.e., increased water savings are associated with the decrease of rainwater demand for toilet flushing and/or with the increase of roof collection area and daily rainfall.

Results of the simulations also confirmed that, for high demand fractions ($d = 2.0$ and $d = 4.0$), the water saving efficiency has an upper limit of 50 and 25%, respectively, with the tank storage fraction having a reduced influence on the system performance. For the other two values of the demand fraction ($d = 0.5$ and $d = 1.0$) the water saving efficiency is much more affected by the tank size and by the rainfall volume.

Results at the daily scale are in agreement with those previously obtained by the same authors (Campisano & Modica 2012) in a regional scale analysis of rainwater tank performances applied to the same region of the case study site.

As the influence of the resolution timescale is considered, the graphs in Figure 5 show that the differences between the simulation results at the daily and sub-daily scales are relatively modest. Curves resulting from simulations run with resolution time steps of 5 min, 15 min, and 1 hour almost overlap in the graphs and show slightly increased tank efficiencies in comparison to those obtained at the daily timescale. Then, the adoption of sub-hourly time steps leads to increased model accuracy. However, differences among the curves start to be significant (more than 5%) only for the high values of *d* (larger than $d = 1$) and for the small values of s (lower than $s = 10$). Such results are in agreement with Mitchell *et al.* (2008) and confirm that the water saving efficiency of the tank (and the model accuracy) is appreciably affected by the time step only for the small storage capacities.

Stormwater retention efficiency

The analysis of the overflow component from the water balance simulation of the tank allowed investigation of the tank behavior with regard to its stormwater retention performance. The behavior of the tank during rain events of different magnitude and time length was focused at the different timescales. To explain the process, in Figure 6 the results of the tank simulation (with a 5 min resolution time step) during the event of 4 August 2006 (total rainfall 33.8 mm, duration 70 min) are reported for $d = 1$ and $s = 5$. The event shows a peak of intensity of 10.8 mm in 5 min at hour 17:10. At the beginning of the event, the tank is empty and during the whole event the toilet is flushed three times (at hours 16:20, 16:30 and 17:05). The figure clearly shows that the rainwater tank basically acts an initial abstraction of volume from the rainfall event up to the achievement (at hour 17:00) of the condition of tank full (the tank retention capacity is saturated). Then, overflows from the tank start to occur. During the overflow process further (small) retention effect is provided by the tank, due to toilet demand.

Globally, the results of all the simulations concerning the retention potential of the tank are summarized in Figure 7. Similarly to results plotted in Figure 5 for water saving, the graphs in Figure 7 report results concerning the tank volumetric retention efficiency E_R. In particular, the four graphs show results for $d = 0.5$, $d = 1.0$, $d = 2.0$ and $d = 4.0$, respectively.

All the graphs indicate that E_R increases as d increases: relatively high water demands and small precipitations keep the tank empty and avoid potential overflows from the system. As well, results of the simulations show that the values of E_R increase as the storage fraction increases.

Analysis of the influence of the resolution timescale on results of the simulations reflects more evident differences among the curves than those obtained for water saving efficiency. The graphs in Figure 7 show that differences

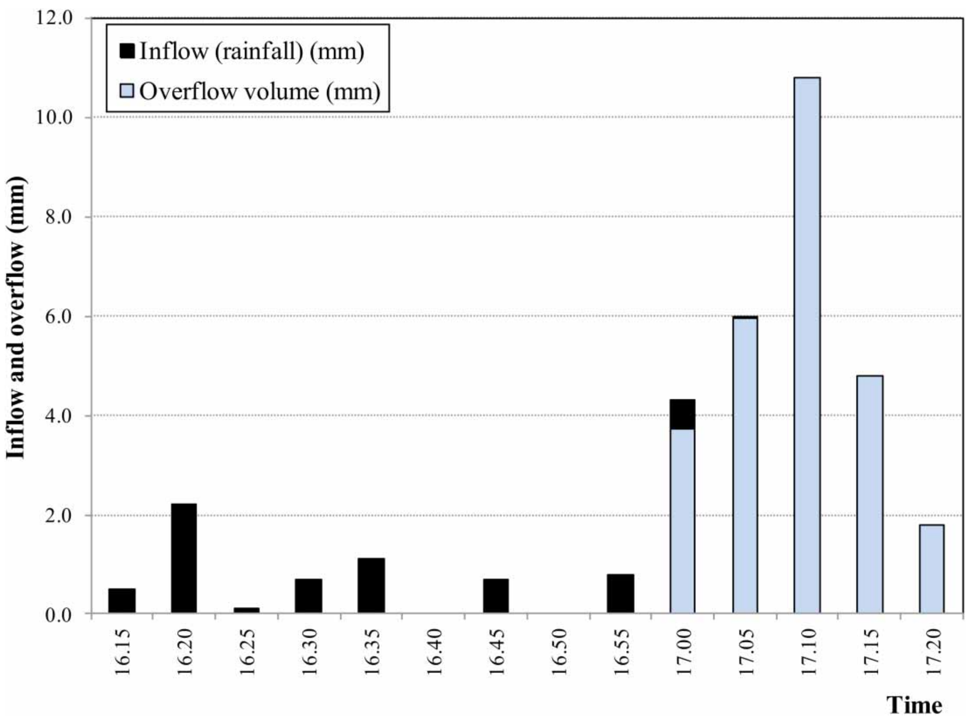

Figure 6 | Simulation of tank retention behavior (time step resolution = 5 min) during the event of 4 August 2006 ($d = 1$ and $s = 5$).

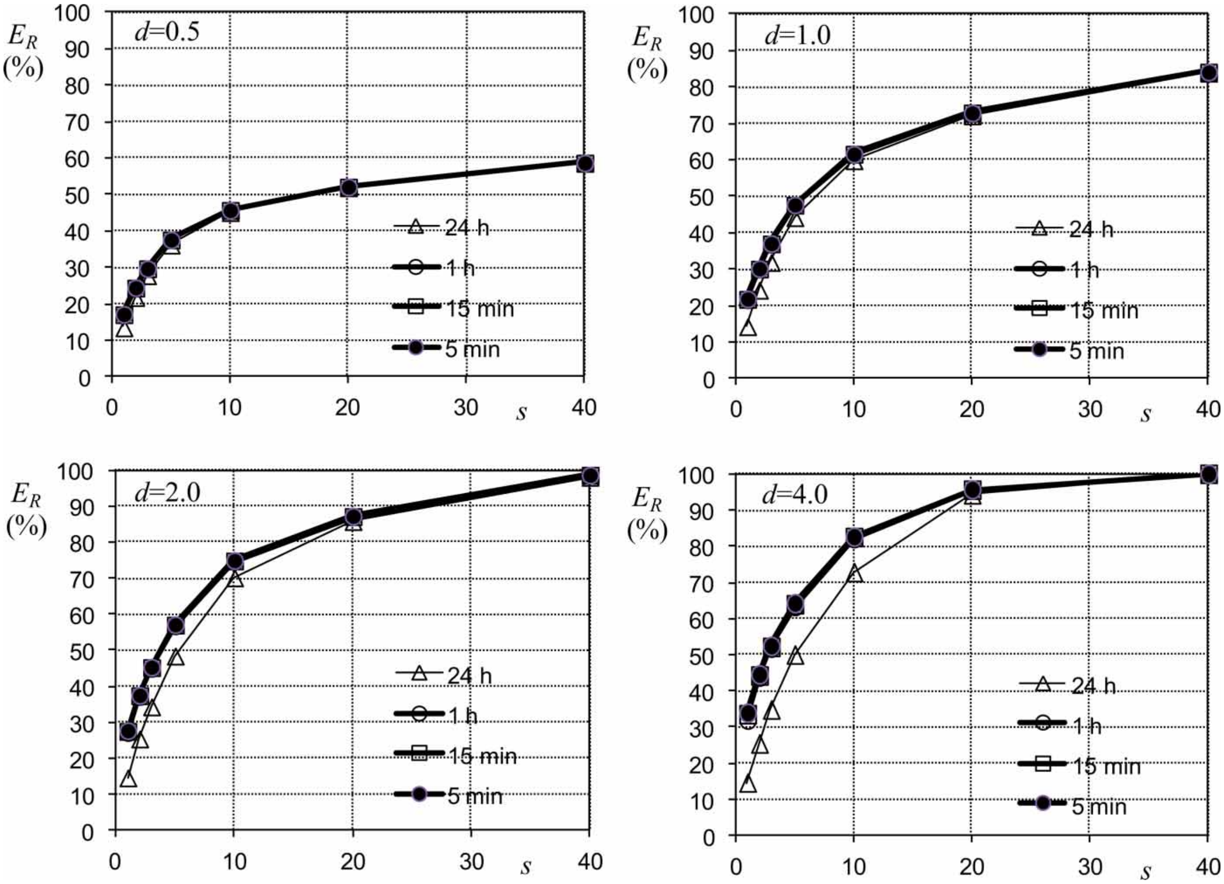

Figure 7 | Evaluation of the volumetric retention efficiency of the tank at the different selected resolution timescales.

increase as s decreases and d increases. In particular, the curves obtained using hourly and sub-hourly temporal resolutions differ significantly (up to 7.5% for $d = 1.0$ and to 17.5% for $d = 4.0$) from those associated with the daily timescale, clearly stressing that a significant gain in accuracy is obtained from the down scaling of the analysis to time resolutions higher than the daily scale. However, curves associated with simulations run using 5 min, 15 min and 1 hour time steps practically overlap each other revealing that, at least for the selected case study, it is not convenient (in terms of computational efforts) to perform analysis of the tank volumetric retention performance at sub-hourly timescales.

Reduction of the rainfall intensity peak

Preliminary analysis was conducted in this paper to explore whether the rainwater tank also has the versatility to reduce peaks of rainfall intensity. For analysis of the peaks only the two temporal resolutions of 5 and 15 min were used.

To better clarify the crux of the question, results of the simulation of the event of 4 August 2006 (the same event discussed in the previous section) for $d = 1$ and for a tank with $s = 15$ (three times larger than that of Figure 6) are reported in Figure 8 (using the 5-min time step). Overflows from the tank are delayed at hour 17:10 due to the increased retention capacity of the tank. More interestingly, the figure shows that the tank also has a positive effect on the reduction of the rainfall intensity peak from 10.8 mm/5 min to about 7.5 mm/5 min.

This analysis was extended to the entire year and the effect of peak reduction was observed to occur for a number of rainfall events, basically depending on the characteristics of each event (i.e., the position of the peak intensity within the event time length) and of the tank (size, pre-event filling condition). Then, assuming the

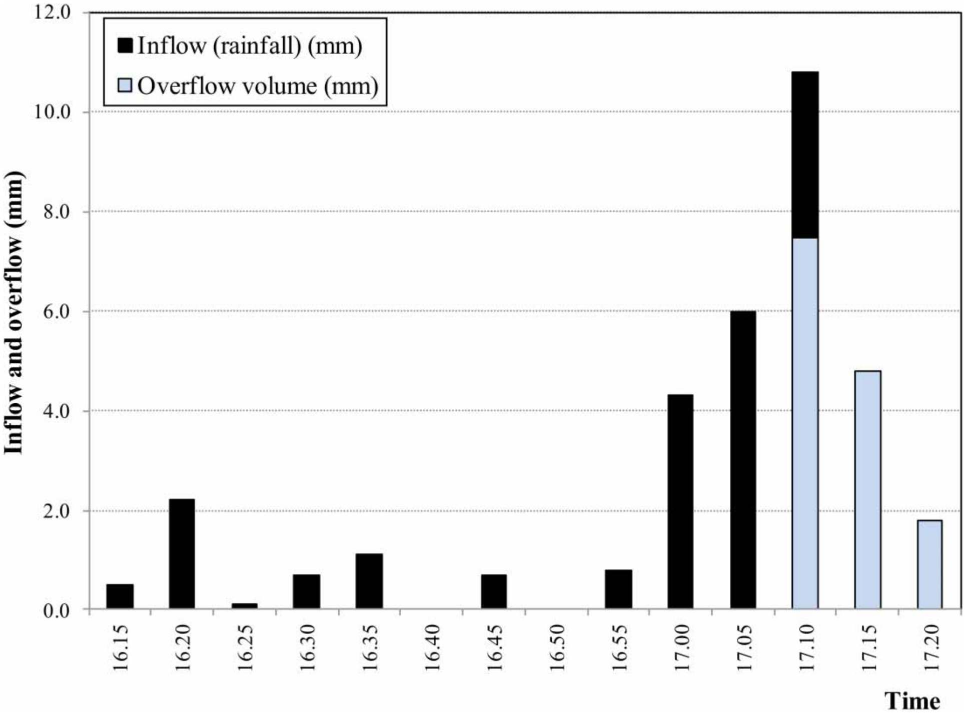

Figure 8 | Simulation of tank retention behavior (time step resolution = 5 min) during the event of 4 August 2006 ($d = 1$ and $s = 15$). Rainfall intensity peak reduction is shown.

events to be independent if they have a minimum antecedent dry weather period of 1 hour, a frequency analysis was conducted to evaluate the events that show a reduction of the rainfall intensity peak.

Results of such analysis are reported in Figure 9 for the exemplificative case characterized by $d = 1$ and $s = 5$. In particular, the peak reduction efficiency E_{PR} is plotted in the figure as a function of the cumulative relative frequency (of exceedance) of rainfall events in the year. As expected, curves decrease monotonically with steep (almost vertical) initial and final queues showing almost 25–30% of the events for which the tank does not provide any reduction of the peak ($E_{PR} = 0$) but also 35–40% of the events with peak being totally abated. The curves also present small derivatives in their mid portion, providing peak reductions of 50% for a number of events ranging between 45 and 50% of the total events. Some differences are encountered between results of the simulations for the two analyzed time resolutions indicating that the model accuracy increases if time step is reduced from 15 to 5 min. Preliminary results presented in Figure 9 pave the way for future research to explore RWH systems peak reduction efficiency for a large range of demand and storage fraction values.

Application example

The following example is presented to show how to use the illustrated methodology in practice. A residential house hosting five people is considered. The net surface rooftop area of the house is $A = 138\ m^2$. The toilet is equipped with a 6-L cistern and each of the five people are considered to flush the toilet six times/day on average resulting in a total daily demand $D = 6 \times 6 \times 5 = 180$ L/day. A rainwater tank with size $S = 0.9\ m^3$ is considered for the RWH system. Average daily rainfall is $475/365 = 1.3$ mm/day. Accordingly, Equation (8) provides $d = D/AR = 0.180/138/0.0013 = 1$ whereas Equation (9) provides $s = S/AR = 0.9/138/0.0013 = 5$.

Assuming the daily scale to be reliably used to evaluate the water saving efficiency, Figure 5 shows $E_{WS} = 47\%$. Similarly, assuming the hourly time resolution, Figure 7 shows that the tank may allow achievement of volumetric retention efficiency close to $E_R = 49\%$. Also, considering

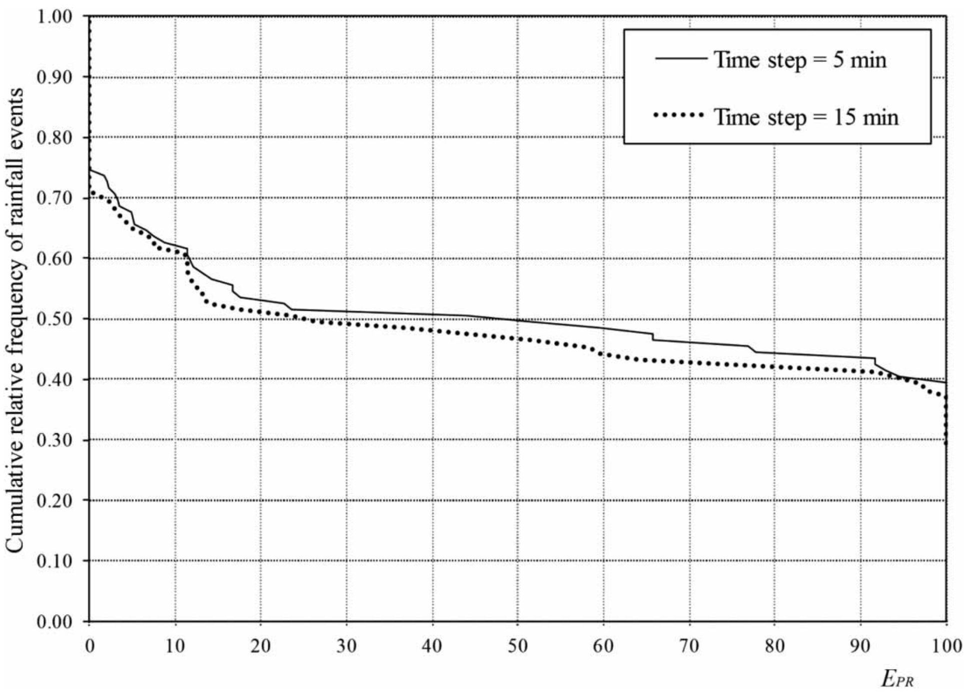

Figure 9 | Peak reduction efficiency E_{PR} as a function of the cumulated relative frequency (of exceedance) of rainfall events in the year ($d = 1$ and $s = 5$).

time step of 5 min, Figure 9 indicates that the tank may abate the peak of the entering hydrograph to zero in 39% of cases with 50% peak reduction ($E_{PR} = 0.5$) in 50% of the rainfall events.

CONCLUSIONS

A contribution to analysis of the performances of tank-based rainwater harvesting systems was presented in this paper. The appropriate temporal scale for modeling the behavior of the tank in relation to its purpose was explored.

A simulation framework allowed modeling of the inflow to the tank (rainfall), the outflow from the tank (toilet water demand), and the water balance simulation of the tank was developed with the possibility of use at different timescales of resolution.

Four temporal scales (daily, 1 hour, 15 min and 5 min time steps) were chosen to assess potential benefits of RWH tanks in terms of both water saving and volumetric retention efficiency. Also, the versatility of the tank to act as a reduction of the rainfall intensity peak was explored.

A pilot household case study for which detailed measurements of water demand data are available was selected to test the model. According to the developed procedures, long-term series of toilet flushes and rainfall were generated at different daily and sub-daily resolution timescales and used as input for the water balance simulation of the tank.

Simulations have basically shown that the daily scale may be reliably chosen to evaluate the tank water saving efficiency, as the result differences among the daily and sub-daily scales are relatively modest (less than 5% for a large range of conditions).

Differently, (at least) the hourly time step resolution is required for a reliable evaluation of tank volumetric retention efficiency. Otherwise, the use of the daily scale may affect result accuracy in a significant way, especially for small tanks and for high values of water demand (differences in efficiency up to about 17%).

Moreover, preliminary results at the 5 min time step showed that the rainwater tank may help reduce the rainfall intensity peak for a relatively high number of rainfall events (50% peak reduction for at least 50% of events), depending on the tank storage and on the rainfall event characteristics.

Results of the investigation may be used by modelers to set up proper simulation of rainwater tanks as part of RWH systems. The used approach also paves the way to the possibility of comprehensively exploring the potential of such systems to reduce peak of rainfall intensity during precipitation events.

The used methodology was applied to a single household and assuming the harvested water to be used only for toilet flushing. Application to buildings of different types characterized by other indoor and outdoor water uses could be explored in the future, potentially leading to different results.

REFERENCES

Abdulla, F. A. & Al-Shareef, A. W. 2009 Roof rainwater harvesting systems for household water supply in Jordan. *Desalination* **243**, 195–207.

Agudelo-Vera, C. M., Keesman, K. J., Mels, A. R. & Rijnaarts, H. H. M. 2013 Evaluating the potential of improving residential water balance at building scale. *Water Res.* **47**, 7287–7299.

Blokker, E. J. M., Vreeburg, J. H. G. & Dijk, J. C. 2010 Simulating residential water demand with 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.

Buchberger, S. G. & Wells, G. J. 1996 Intensity, duration, and frequency of residential water demands. *J. Water Resour. Plann. Manage.* **122** (1), 11–19.

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. 2014 Selecting time scale resolution to evaluate water saving and retention potential of rainwater harvesting tanks. *Proc. Eng.* **70**, 218–227.

Campisano, A., Gnecco, I., Modica, C. & Palla, A. 2013 Designing domestic rainwater harvesting systems under different climatic regimes in Italy. *Water Sci. Technol.* **67** (11), 2511–2518.

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.

Dunker, L. 2001 The KAP Tool for Hygiene. A Manual on: Knowledge, Attitudes and Practices in the Rural Areas of South Africa. WRC Report No. TT 144/00. Water Research Commission, Pretoria, South Africa.

Farreny, R., Morales-Pinzón, T., Guisasola, A., Tayà, C., Rieradevall, J. & Gabarrell, X. 2011 Roof selection for rainwater harvesting: quantity and quality assessment in Spain. *Water Res.* **45** (10), 3245–3254.

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. J., 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.

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.

Heyworth, J. 2001 A diary study of gastroenteritis and tank rainwater consumption in young children in South Australia. In: *Proceedings of the 10th International Rainwater Catchment Systems Conference, 10–14 September 2001*, Mannheim, Germany, pp. 141–148.

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, David, CA, USA.

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.

Lazarova, V., Hills, S. & Birks, R. 2003 Using recycled water for non-potable, urban uses: a review with particular reference to toilet flushing. *Water Sci. Technol. Water Supply* **3** (4), 69–77.

Leusbrock, I., Agudelo-Vera, C. M., Keesman, K. J., Zeeman, G. & Rijnaarts, H. H. M. 2013 Application of urban harvest approach on water and resource cycles: how to quantify the impacts of water saving measures and innovative water technologies and concepts? In: *Proceedings of 3rd IWA Young Water Professional Conference, Benelux*, Belval, Luxembourg.

McMahon, T. A., Adeloye, A. J. & Zhou, S. L. 2006 Understanding performance measures of reservoirs. *J. Hydrol.* **324** (1–4), 359–382.

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. Software* **23**, 782–793.
Morales-Pinzón, T., Lurueña, R., Gabarrell, X., Gasol, C. M. & Rieradevall, J. 2014 Financial and environmental modelling of water hardness – implications for utilising harvested rainwater in washing machines. *Sci. Total Environ.* **470–471** (2014), 1257–1271.
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.
Sturm, M., Zimmermann, M., Schütz, K., Urban, W. & Hartung, H. 2009 Rainwater harvesting as an alternative water resource in rural sites in central northern Namibia. *Phys. Chem. Earth* **34** (13–16), 776–785.
Van der Sterren, M., Rahman, A. & Dennis, G. 2013 Quality and quantity monitoring of five rainwater tanks in Western Sydney, Australia. *J. Environ. Eng.* **139** (3), 332–340.
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.

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